

AD-771 030

TURBINE ENGINE FUEL CONTROL RELIA-
BILITY AND MAINTAINABILITY ANALYSIS

Dennis G. Burnell, et al

Colt Industries, Incorporated

Prepared for:

Army Air Mobility Research and Development
Laboratory

August 1973

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Unclassified

Security Classification

AD 771030

DOCUMENT CONTROL DATA - R & D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) Colt Industries Inc. Chandler Evans Control Systems Division West Hartford, Connecticut		2a. REPORT SECURITY CLASSIFICATION Unclassified
		2b. GROUP
3. REPORT TITLE TURBINE ENGINE FUEL CONTROL RELIABILITY AND MAINTAINABILITY ANALYSIS		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report		
5. AUTHOR(S) (First name, middle initial, last name) Dennis G. Burnell Terry B. Morrison Albert H. White		
6. REPORT DATE August 1973	7a. TOTAL NO. OF PAGES 159 / 161	7b. NO. OF REFS 28
8a. CONTRACT OR GRANT NO. DAAJ02-72-C-0110	9a. ORIGINATOR'S REPORT NUMBER(S) USAAMRDL Technical Report 73-60	
b. PROJECT NO. 1F162205A11902	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
c.		
d.	Chandler Evans Report R-673-9	
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.		
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Eustis Directorate U. S. Army Air Mobility R&D Laboratory Fort Eustis, Virginia
13. ABSTRACT This fuel control analysis was undertaken to establish cost-effective recommendations for improving the design life and maintainability of Army gas turbine engine fuel control systems. Army experience indicates that problems with the fuel control account for 10 to 13% of the engine malfunctions and that 30 to 50% of the fuel control removals are unjustified. Data collected indicates that failure modes common to the majority of all present-day fuel controls account for about 25% of the control removals. These failure modes included susceptibility to air and fuel contamination, fuel seal leaks, wear of drive splines, and improper adjustments. Insufficient detailed data is available to determine the causes for removal of the remaining 25% of the fuel controls. Information indicates that the causes are random and are probably associated with assembly and other human-error-related problems. Design studies on both built-in and ground support types of fault-isolation devices which would signal when a control removal was warranted were completed. These studies indicate that, for present-day fuel controls, only the ground support type fault-isolation system which can be shared by 5 or more aircraft would be cost effective. In consideration of future electronic fuel control systems, the studies show that built-in fault isolation can be cost effective. Incorporation of the recommended design improvements for alleviating failure modes offers the potential for future fuel controls to meet a goal of providing 5000 hours of operation between overhauls. The effective use of fault isolation offers reduced life-cycle costs and increased aircraft availability.		

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Springfield, VA 22151

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fuel Control Analysis						
Fault-Isolating Fuel Controls						
Improving Life and Maintainability of Fuel Controls						

ib

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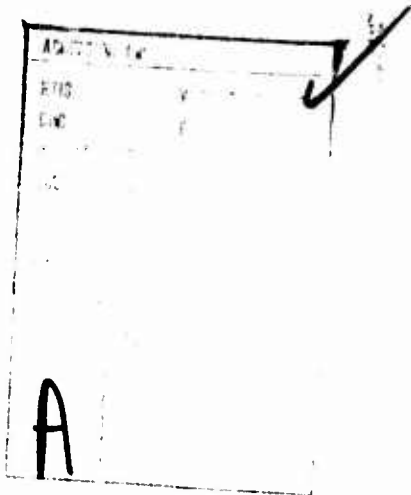
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EUSTIS DIRECTORATE
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This report was prepared by the Chandler Evans Control Systems Division of Colt Industries, Incorporated, under the terms of Contract DAAJ02-72-C-0110. It presents the results of an analytical effort to determine the causes of inherent turbine engine fuel control failure modes and to determine the most cost-effective means of accurate fault isolation when a fuel control malfunction is suspected.

The objectives of this contractual effort were (1) to analyze current model fuel control failure modes to determine definitive causative factors and to make detailed recommendations applicable to current or future engine controls to preclude recurrence of such failures, and (2) to analyze existing turbine engine fuel control concepts to make recommendations for non-ambiguous, cost-effective fuel control fault isolation provisions.

The program objectives were generally met. The analysis shows that firm design recommendations for certain generic failure modes cannot be made until certain advanced concepts have been tested. Ultrafine input fuel filtration and new-design fuel seals are in this category. The analysis of fault isolation provisions and methods is quite thorough and comprehensive. It is concluded that the most practical device to fault isolate a purely hydromechanical fluid controller is a gauge to sense the pressure across the metering valve. Since the likelihood is high that future control systems will use electronic devices for flow schedule computation, the recommendation for built-in testing is valid.

This report has been reviewed by the appropriate technical personnel of this Directorate, who concur with the conclusions contained herein. The U. S. Army Project Engineer for this effort was Mr. R. L. Campbell, Sr., of the Military Operations Technology Division.

Task 1F162205A11902
Contract DAAJ02-72-C-0110
USAAMRDL Technical Report 73-60
August 1973

TURBINE ENGINE FUEL CONTROL
RELIABILITY AND MAINTAINABILITY ANALYSIS

Final Report

Chandler Evans Report R-673-9

By

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Prepared by

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for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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ABSTRACT

This fuel control analysis was undertaken to establish cost-effective recommendations for improving the design life and maintainability of Army gas turbine engine fuel control systems. Army experience indicates that problems with the fuel control account for 10 to 13% of the engine malfunctions and that 30 to 50% of the fuel control removals are unjustified.

Data collected during the study indicates that failure modes common to the majority of all present-day fuel controls account for about 25% of the control removals. These failure modes included susceptibility to air and fuel contamination, fuel seal leaks, wear of drive splines, and improper adjustments. Insufficient detailed data is available to determine the causes for removal of the remaining 25% of the fuel controls. Information indicates that the causes are random and are probably associated with assembly and other human error related problems.

Design studies on both built-in and ground support types of fault isolation devices which would signal when a control removal was warranted were completed. These studies indicate that, for present-day fuel controls, only the ground support type fault isolation system which can be shared by five or more aircraft would be cost effective. In consideration of future electronic fuel control systems, the studies show that built-in fault isolation can be cost effective.

Incorporation of the recommended design improvements for alleviating failure modes offers the potential for future fuel controls to meet a goal of providing 5000 hours of operation between overhauls. The effective use of fault isolation offers reduced life-cycle costs and increased aircraft availability.

FOREWORD

This is the final report covering work completed under Contract DAAJ02-72-C-0110, DA Task 1F162205A11902, during the period June 30, 1972 to March 31, 1973.

The program was conducted under the technical direction of Mr. R. L. Campbell, Sr., Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia. The work was completed by Colt Industries, Inc., Chandler Evans Control Systems Division, under the cognizance of Mr. D. F. Wills, Vice President of Engineering, and Mr. J. M. Maljanian, Manager, Engine Controls. Mr. A. H. White was the Program Manager. Acknowledgment is given to the following organizations for the information they contributed to this program.

Army Aeronautical Depot Maintenance Center
Army Aviation Systems Command
Army Agency for Aviation Safety
Aviation Power Supply
AVCO-Lycoming
Bell Helicopter
Boeing-Vertol
Fluid Power Research Center, Oklahoma State University
Hughes Aircraft
Kaman
Pacific Air Motor
Pall Corporation
Pratt & Whitney Aircraft, Canada
Pratt & Whitney Aircraft, East Hartford
Sikorsky Aircraft
Teledyne Ryan Aeronautical
Williams Research

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LIST OF SYMBOLS

A	logic failure level, WA threshold reference
AC	alternating current
BIT	built-in test
C	cost of fuel control unit
Cs	cost per 1,000 flight hours
C/P	collective pitch angle
DC	direct current
3D	three dimensional
E_F	error, fuel flow
E_H	error limit, high
E_L	error limit, low
E_P	error, pressure
E_V	error, valve position
FID	fault-isolation device
FMEA	failure mode and effect analysis
GITE	ground integrated test equipment
GSTU	ground support test unit
GTE	ground test equipment
GVH	guide vane high limit, threshold reference
GVL	guide vane low limit, threshold reference

H1	logic failure level, WH_1 threshold reference
H2	logic failure level, WH_2 threshold reference
IGV	inlet guide vane angle
IGV*	inlet guide vane angle, computed
IGV(1)	inlet guide vane angle, self-test parameter
KG	gas generator speed governor gain
KN_2	power turbine governor gain
L	life cycle in flight hours
L1	logic failure level, WL_1 threshold reference
L2	logic failure level, WL_2 threshold reference
LVDT	linear variable differential transformer
MMV	main metering valve
MTBR	mean time between removals
MTBF	mean time between failures - where a failure is defined as any maintenance action
MTTR	mean time to repair
N_1	gas generator speed
N_1 ()	gas generator speed, self-test parameter
N_2	power turbine speed
N_2 ()	power turbine speed, self-test parameter
N_2^*	power turbine set speed
N_2^* ()	power turbine set speed, self-test parameter
NH	high-speed limit, threshold reference

NL	low-speed limit, threshold reference
P_1	atmospheric pressure
P_2	compressor inlet pressure
P_2 (1)	compressor inlet pressure, self-test parameter
P_3	compressor discharge pressure
P_F	fuel pump discharge pressure
PLA	pilot's power lever angle
PLA ()	pilot's power lever angle, self-test setting
PLAN ₂	pilot's power turbine speed-select lever
P_N	metering valve fuel downstream pressure
P_S	servo pressure
PW	pulse width
Q_L	engine output torque, local
Q_R	engine output torque, remote (twin engines)
ROM	read-only memory
rpm	revolutions per minute
T_1	atmospheric temperature
T_2	compressor inlet temperature
T_2 (1)	compressor inlet temperature, self test
T_4	turbine inlet temperature
T_4^B	turbine blade temperature
TRFID	threshold reference fault-isolation device

VCO	voltage-controlled oscillator
VH	logic failure level, GVH threshold reference
VL	logic failure level, GVL threshold reference
WA	acceleration fuel flow, threshold reference
W_F	fuel flow
W_F^*	fuel flow, computed
WH1	fuel flow high limit, start-to-idle threshold reference
WH2	fuel flow high limit, N_2 governor threshold reference
WL1	fuel flow low limit, start-to-idle threshold reference
WL2	fuel flow low limit, N_2 governor threshold reference
X_m	metering valve position, measured
X_m^*	metering valve position, computed
$X_m^*_1$	metering valve position, computed for N_1 speed governing
$X_m^*_2$	metering valve position, computed for N_2 speed governing
$X_m ()$	metering valve position, self-test parameter
$X_m^*_{ACC}$	metering valve position, computed for acceleration
$X_m^*_{DEC}$	metering valve position, computed for deceleration
$X_m^*_{MAX}$	metering valve position, computed for maximum limit
ΔP	pressure drop across metering valve

ΔP (1)	pressure drop across metering valve, reference value
ΔP^*	pressure drop across metering valve, computed
μ	micron
τN_2	power turbine governor lag time constant

INTRODUCTION

Field usage data on various Army turboshaft engines indicated that 10 to 13 percent of the confirmed engine failures are in the fuel control, and that only 30 to 50 percent of the control removals were verified as failures. Present production fuel controls cost 7 to 10 percent of the total engine delivery price to the Army, and fuel control maintenance consumes an average of about 11 percent of the man-hours spent on the engine. The high occurrence of unscheduled and unjustified fuel control removals detracts from the reliability and availability of the aircraft and substantially increases life-cycle costs.

The turbine engine fuel control reliability and maintainability analysis reported herein was undertaken to establish recommendations for design improvements to reduce failure modes and fault isolation devices to reduce unjustified removals. The study was conducted in three phases.

The first phase was directed toward identifying and analyzing fuel control system generic failure modes to establish design recommendations for eliminating these failures in present and future control systems. Information on control failures was obtained from available Army and Navy reports and from surveys of various Army agencies and fuel control users. However, present Army and Navy reliability and maintainability field data retrieval systems and overhaul procedures on fuel control do not provide sufficiently detailed information to verify the causes for removal. Therefore, it was necessary to rely primarily on information obtained from survey discussions and in-house experience at Chandler Evans.

The major failure modes identified as being common to most fuel controls consist of malfunctions due to air and fuel contamination, static and dynamic seal leaks, drive spline wear, and improper adjustments.

The second phase of work was directed toward establishing a cost-effective fault isolation device which would indicate when a control removal was warranted. Army field maintenance capabilities on fuel controls are limited to making speed adjustments and removing and replacing the fuel control. Consequently, 30 to 50% of the removals are unjustified based on subsequent depot bench test experience.

An effective fault isolation device will significantly reduce unjustified removals and the maintenance man-hours spent in troubleshooting controls. Because a number of different fault isolation devices of varied complexity can be conceived, substantial preliminary work was done to establish guidelines for allowable costs. This work indicated that a 100% effective fault isolation device costing about 12% of the production price of the fuel control is the cost-effective break-even point. The studies concluded that for present-day fuel controls, only ground support type fault isolation equipment shared by five or more aircraft would be cost effective. In considering future electronic fuel controls, built-in fault isolation will be cost effective. This is possible because signals of all of the required parameters needed for fault isolation are available in an electronic control.

The third phase of effort was carried out to evaluate the potential improvements in the design life and maintenance requirements of a typical control system that could be achieved by incorporating all of the design recommendations for reducing failure modes and effective use of a fault isolation device. This evaluation indicates that the design life of future fuel controls can meet a goal of 5000 hours of operation between overhauls.

The Chandler Evans TA-2S fuel control used on the Lycoming T-53 engine was selected for this detailed evaluation because more data was available on this control than on any other, and it is the most prevalent control, in quantity, in the Army inventory.

The fuel controls which were considered in this study include those used on the T53, T55, T63, T73 and T74 Army turboshaft engines.

DISCUSSION

FAILURE MODE ANALYSIS

The purpose of this part of the program was to identify control system faults, so that design studies and recommendations could be made to increase the control system reliability and to improve maintainability features.

Fuel Control Systems Investigated

To understand the types of failures which exist in gas turbine control systems, it is necessary to understand the basic operation of the controls. The controls of the T53, T55 and T73 are similar in principle. These are hydromechanical control systems and use fuel pressure to actuate power servos for computing the allowed fuel flow. The controls for the T63 and T74 are pneumomechanical systems and use engine compressor air pressure as the medium for computing fuel flow. This causes a basic difference in service. In the systems using fuel for servo power, the fuel can be filtered to provide long life of the control system, whereas the air systems cannot be filtered without some sacrifice in control system performance, because the pressure drop across the filter varies with time in service.

Fuel Control System Descriptions

The following is a description of the basic operation of each control system considered.

T53 Engine Control - Refer to Figure 1

The T53 engine fuel control is the only control used by the Army which integrates, into one package, the pumps and fuel control system.

The package contains the fuel metering elements in one housing and fuel flow computation in another housing, which is bolted to the fuel metering housing. The power turbine governor is connected to the hydromechanical computer and may be changed separately in the field.

The functions which the control provides are:

1. Power turbine speed governor
2. Gas generator speed governor
3. A pilot-operated manual system
4. Acceleration control in which acceleration fuel flow is controlled as a function of N_1 , T_2 and P_2
5. Deceleration control using the same engine parameters as for acceleration
6. Transient compressor bleed control. This function provides control of compressor surge during engine acceleration. A measure of $(W_f/P_2 \text{ accel} - W_f/P_2 \text{ steady state})$ is used to modulate the compressor bleed actuator.
7. Compressor inlet guide vanes are positioned as a function of N_1 and T_2 .

The basic functions are represented in block form in Figure 2.

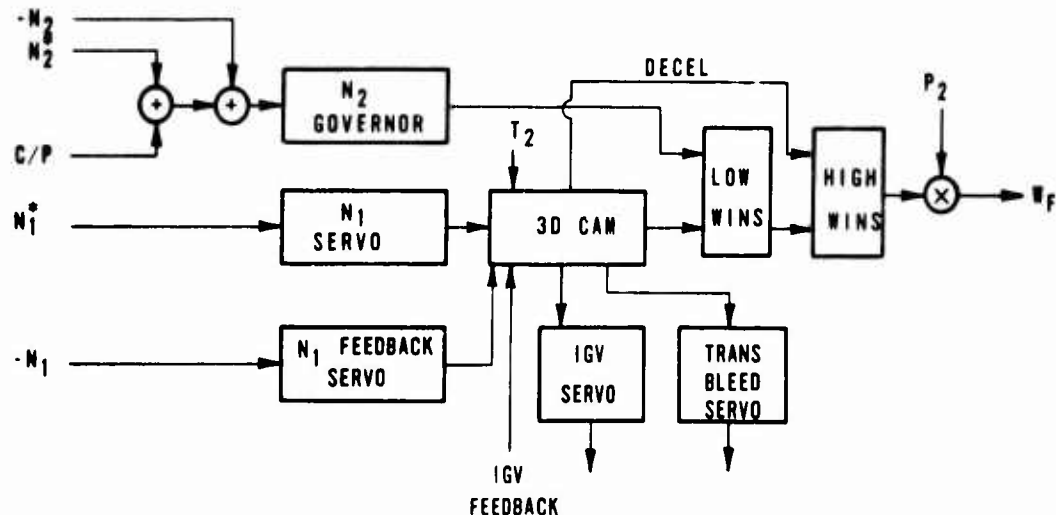


Figure 2. T53 Engine Control Block Diagram.

Hydromechanical Computer

The N_1 servo is a position servo in which the pilot's demand N_1^* is compared to the sensed N_1 signal. The speed error is amplified using a four-way servo valve operated piston with position feedback. The position of the piston is used to close the loop on the servo.

The N_1 feedback servo translates the three-dimensional cam. The servo is a force feedback system so that calibration adjustments may be made by adjusting internal spring loads. The four-way spool valve is rotated to minimize hysteresis, and speed is sensed by conventional flyweights.

The 3D cam is rotated as a function of T_2 by a P-cymene filled motor bellows. The stroke of the T_2 motor bellows is determined by fuel temperature compensated by summation with another bellows.

The N_2 speed computer is also a force balance servo. The feedback linkage and cam include a variable gain to provide dynamic compensation at different power levels. The W_F/P_2 outputs of the acceleration schedule N_1 and N_2 governors pass through a "lowest wins" mechanism. This signal is then multiplied by P_2 by a multiplying linkage. The P_2 position input to the multiplier is from a force feedback P_2 servomechanism. P_2 is sensed with an evacuated bellows. The sleeve of the P_2 servo is rotated. The output of the multiplier positions the fuel metering valve.

Fuel metering is through triangular slots cut into a cylindrical valve. As the metering valve is stroked, the areas of the slots vary linearly.

The compressor transient bleed valve control signal is taken from the 3D cam and varies the air pressure in the engine bleed actuator open loop.

The compressor inlet guide vane schedule is also taken from the 3D cam through a hydraulic servo valve. The IGV actuator is engine mounted, and its position is fed back to the control to null the servo valve.

Fuel Pumping System

Fuel enters the system through a 76-micron screen. It is then passed through two gear pumps driven in parallel from the engine gas generator. Each gear pump is capable of providing full engine fuel flow. The fuel flows from the pumps through check valves (3 psi) which prevent a short circuit if one pump fails. The fuel then passes through the main fuel filter. This comprises, in one assembly, a 140-micron screen for the main fuel flow and an inner paper element (25-micron absolute and 9-psi bypass valve) to provide clean high-pressure fuel to actuate all the computer servos. A check valve (24 psi) is the next component in line, which ensures that the servo pressure is sufficiently high when operating on the manual system. Fuel then flows into the main metering valve, and the pressure drop across this valve is held essentially constant by a bypassing head regulator. The head across the metering valve is sensed across a diaphragm which, if the set value is exceeded, moves to bypass fuel to the pump inlet. The nominal setting for the head regulator is 20 psid, and an external adjustment is provided for different fuel types. The fuel passes through another check valve (3.5 psi), which prevents flow reversal when on the manual system. The next component is the foot valve which is referenced to computer case pressure (60 psid), ensuring that there is always enough servo pressure to operate the servos accurately in the automatic mode. Fuel then flows out of the control to the engine through the fuel shutoff valve. The pilot lever input allows bypass of fuel back to computer case pressure during normal shutdown.

The manual system is independent of the automatic system. It has a separate head regulator (40 psid) and metering valve. It is selected by operation of a solenoid which ports fuel through the manual metering valve, which is a rectangular orifice cut in the shaft from the pilot's N_1 input. This gives a schedule of fuel flow against PLA. At high altitude it is necessary to throttle back before changing over to manual control to avoid overfueling. The manual system head regulator also incorporates a high-pressure relief valve (850 psi).

Field Adjustments Allowed (T53)

Ground Idle
Military Power
 N_2 min and max flow stops

T55 Engine Control - Refer to Figure 3

As mentioned previously, the T55 fuel control is similar in type and complexity to the Chandler Evans TA-2S (T53). The differences are more in individual company design preferences than fundamental ones.

The control provides:

1. Power turbine speed governing, $N_2 = f(P_3, N_2^*, C/P)$
2. Gas generator speed governing, $N_1 = f(P_3, T_2, N_1^*)$
3. Acceleration control (Fuel flow is controlled as a function of N_1 , T_2 and P_3 .)
4. Deceleration control parameters as (3)
5. Transient compressor bleed, $\text{bleed} = f(W_f/P_3 \text{ accel}, W_f/P_3 \text{ steady state})$

There is no manual or variable IGV in this system. An IGV system is provided on the T55-L-11 but has not been shown on the schematic. No IGV's were provided on earlier engines. It is not necessary to provide a manual system since the application is a twin-engine helicopter in which single-engine operation can sustain flight.

It is noted that the T55 engine uses W_f/P_3 as the control mode as compared to W_f/P_2 for the T53. The advantages and disadvantages of these control modes are enough of a subject for a complete study. However, the W_f/P_3 mode tends to be self compensating for engine compressor deterioration. On the acceleration schedule, as the compressor deteriorates, the surge margin reduces and a W_f/P_3 schedule would inherently provide less fuel flow. A disadvantage of the W_f/P_3 mode is that it provides an inner feedback loop which makes analysis and faultfinding more difficult.

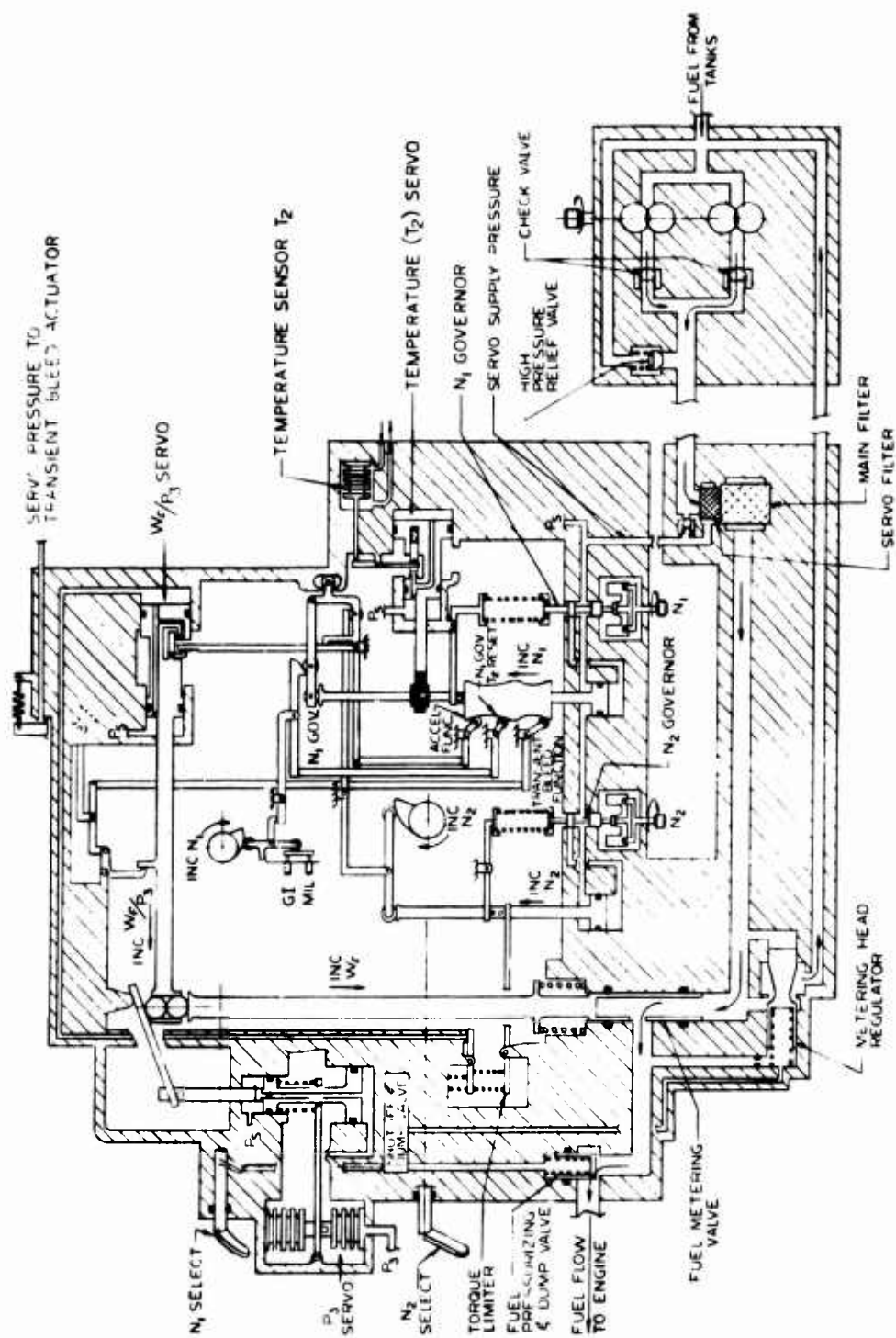


Figure 3. T55 Engine Control Schematic.

The other main differences are that the N_1 and N_2 servos are three-way valves which cost less to produce than four-way valves but require half area actuator pistons which are larger. The output of the computer is to position levers which operate a flapper servo. The flapper servo then drives the fuel metering valve through a P_3 tangent multiplier mechanism. Flapper servos as compared to spool valves also cost less to produce and have long life, but have lower pressure gains and higher steady-state leakage. In their application to the T55, the inputs to the flapper are positions, and hence they do not need compensation for variation in flapper forces due to variation in fuel pressure. The metering valve is linear; that is, fuel flow is directly proportional to stroke. The head regulator is a bypassing type but with no diaphragm to amplify the force, since the metering head is higher than the TA-2 (42 psi). Maximum metered fuel flow is in the order of 2000 lb/hr.

The separately mounted fuel pumping unit has dual-element gear pumps.

Field Adjustments Allowed (T55)

Gas generator max speed

Ground idle

Fuel type (metering head Δp)

Interstage bleed cutoff

T63 Engine Control - Refer to Figure 4

The functions provided by the T63 control are:

1. Power turbine speed governing, $W_f = f(N_2^*, C/P, P_3)$
2. Gas generator speed governing, $W_f = f(N_1^*, P_3)$
3. Acceleration control, $W_f = f(N_1, P_3)$
4. Deceleration control, $W_f = f(N_1, P_3)$

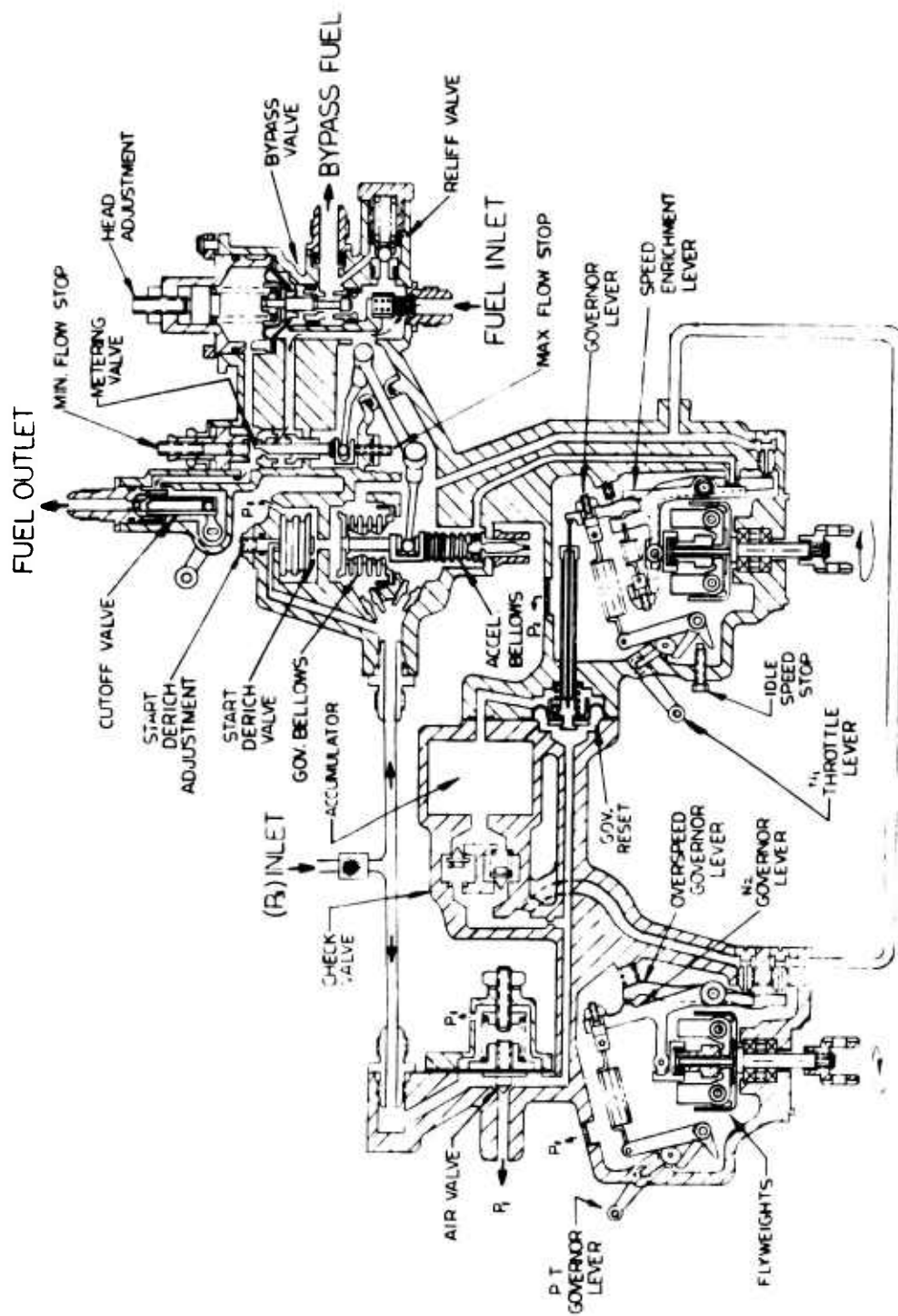


Figure 4. T63 Engine Control Schematic.

The power turbine governor, gas generator control, and fuel pumps are three separate packages.

Fuel is pumped by a dual-element gear pump and is metered by a slab cut valve. The metering head is sensed across a diaphragm which operates a valve to bypass fuel flow in excess of engine demand back to the pump inlet.

The computation of the required engine fuel flow for a given flight condition is performed by using engine compressor air as the computing medium. Air is taken from the engine compressor (P_3) through a barrier filter and provided to both the power turbine governor and the gas generator control. The function of both the gas generator and the power turbine governor is to control the pressure drop across a pair of bellows in series. One bellows is used for governing; the other, for acceleration control. The stroke of the bellows is converted to metering valve stroke through a torsion tube, which allows a fuel to air seal without the use of a dynamic seal.

The power turbine governor compares the force of a fly-weight system with a spring force. The difference is a measure of N_2 speed error which is used to open a flapper valve. This causes a drop in pressure on a diaphragm. The diaphragm has a rod attached to it which is actuated through a "lowest wins" valve from the gas generator governor to reduce fuel flow with an increase in power turbine speed. The accumulator and the check valve system are required to attenuate the dynamic characteristics of the helicopter rotor system.

Gas generator governing and acceleration control operate in a similar way to decrease and increase fuel flow respectively.

The N_1 , N_2 governor and acceleration act on the downstream series of orifices; the upstream pressure being P_3 , the bellows senses the pressures between the orifice pair. The result is that the N_1 , N_2 governor and acceleration control operate on W_f/P_3 ratio units.

Field Adjustment Allowed (T63)

Ground idle

N_1 maximum

Start derichment

N_2 maximum

T73 Engine Control - Refer to Figure 5

This control is similar to the T55 in complexity. It is the largest of the Army controls (maximum flow in the order of 3600 lb/hr). The functions provided by the fuel control are:

1. Gas generator speed governing, $W_f = f(N_1^*, P_3)$
2. Acceleration control, $W_f = f(N_1, P_3)$
3. Deceleration control, $W_f = f(N_1, P_3)$
4. Power turbine speed governing, $W_f = f(N_2^*, C/P)$
5. Engine starting compressor air bleed

The general operation of this fuel control is similar to the T55 engine control described on page 9. The main differences are:

- The 3D cam is not rotated with temperature T_2 .
- The metering valve drive is by a force balance multiplier with P_3 as compared to a tangent multiplier for the T55 control.
- The metering head regulator is servo operated.

Field Adjustments Allowed (T73)

Ground idle

N_1 maximum

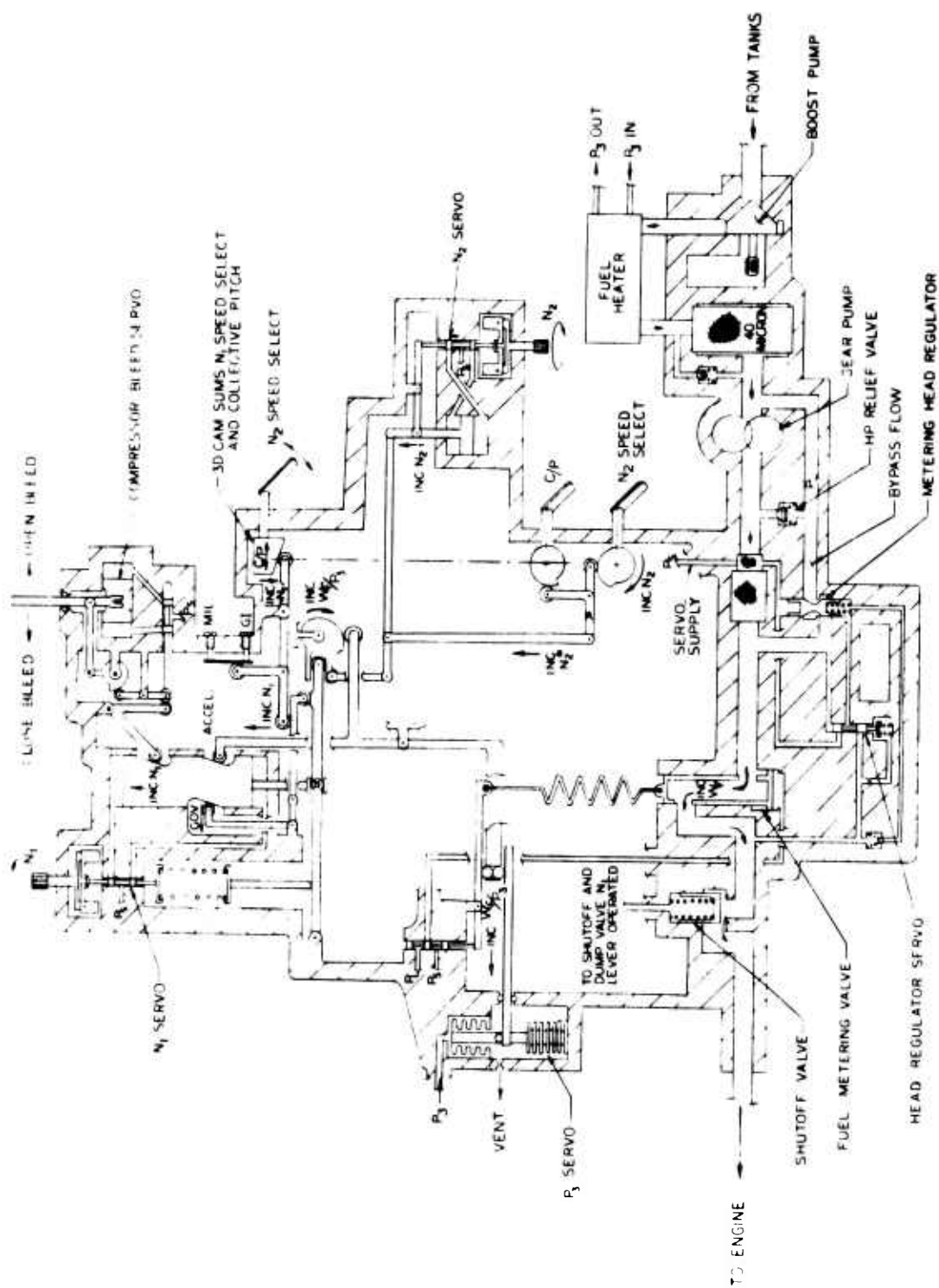


Figure 5. T73 Engine Control Schematic.

T74 Engine Control - Refer to Figure 6

This fuel control is similar to the T63 engine control. The only functional difference is that the acceleration schedule is biased by engine compressor inlet temperature (T_2). The control functions are:

1. Gas generator speed governing
2. Acceleration control
3. Deceleration control
4. Propeller speed governing

Field Adjustments Allowed (T74)

Ground idle

N_1 maximum

N_2 maximum (propeller speed)

Metering valve ΔP for

- a. fuel type
- b. surge margin

Data Procurement

To identify control system failures, a survey of control system users was made. The information received was in the form of reports, verbal discussions, and fuel control R&M data computer printouts. An example of computer data is given in Table I. This is taken from the Navy's 3M data system. The MTBF and MTBR data presented does not necessarily give the relative merits of the controls because of such things as:

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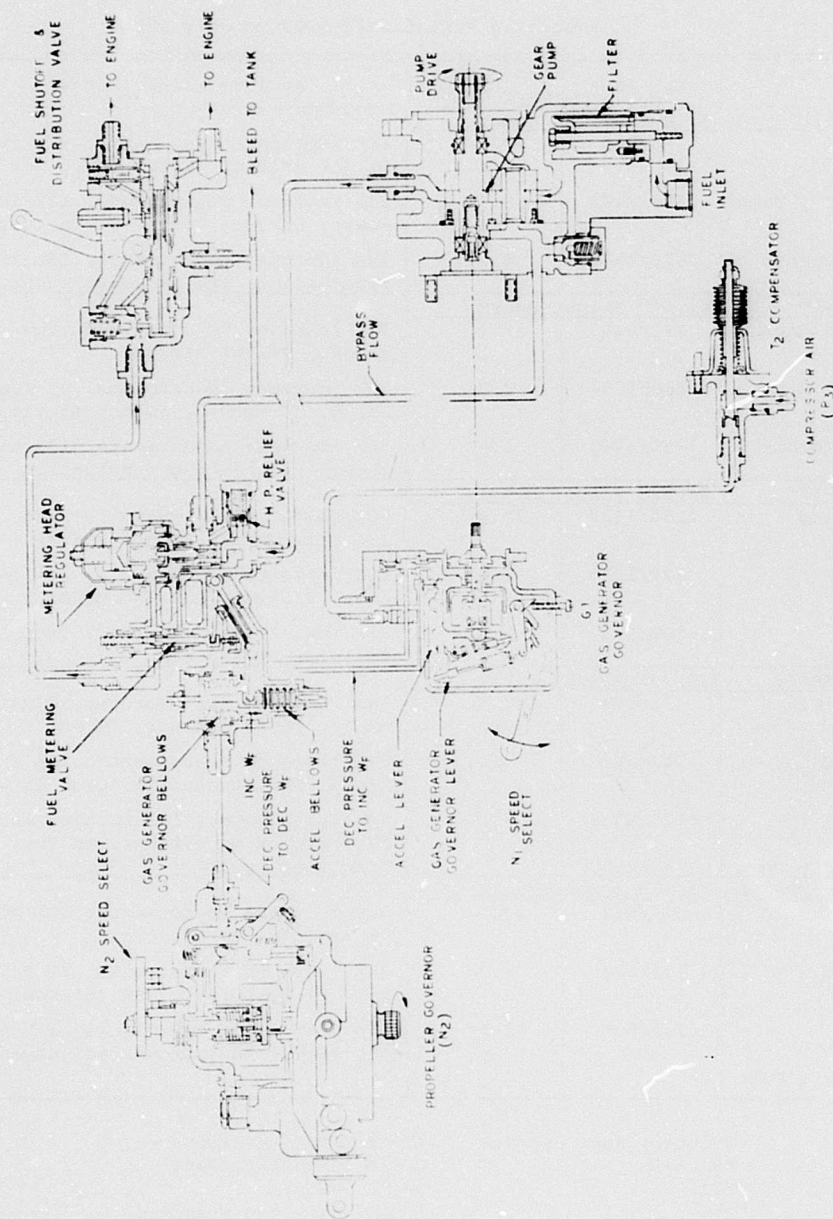


Figure 6. T74 Engine Control System.

TABLE I. SUMMARY OF MAINTENANCE & RELIABILITY DATA SUPPLIED BY KAMAN (NAVY 3M DATA SOURCE) Reporting Period July 1969 to July 1971			
	MTBF/MTBR	Organiz'l MH/1000 FH	Failure Modes (Top 4)
Bell UH-1E 33,894 Flight Hours			
T53-L-11	176/391	70.3	18% improper adjustments, 9% dirty, 7% hot starts, 7% FOD
Main F/C & Pump	389/1767	8.5	51% improper adjustments, 11% low power, 6% fuel leaks, 6% failure unk
P.T. Governor	3638/15460	4.0	29% improper adjustments, 25% rpm fluctuation, 12% improper maint.
Bell AH-1G 21,500 Flight Hours			
T53-L-13 Engine	272/428	57.3	13% leaking, 7% dirty, 7% slow accel., 7% hot starts
Main F/C & Pump	630/2994	2.8	82% improper adjustments, 8% fuel leaks, 3% broken, 3% hot starts
P.T. Governor	1330/4790	1.5	56% improper adjustments, 17% torque incorrect, 12% rpm fluctuation
Bell TH-57 28,828 Flight Hours			
T63 Engine	1254/1923	70.4	26% contam., 17% magnetic plug, 13% failed unk, 5% hot starts
Main F/C	324/1373	9.9	56% improper adjustments, 12% failed unk, 12% fuel leak, 5% binding
Pump	489/930	6.0	78% fuel leaks, 7% dirty, 3% broken, 3% internal failure
Boeing CH46D 100,361 Flight Hours			
T58 Engine	132/223	141.4	18% leaking, 12% improper adjustments, 7% failed unk, 7% FOD
Main F/C	912/3860	3.9	37% improper adjustments, 19% fuel leaks, 5% internal failure, 4% worn
Pump	5576/8363	2.2	44% fuel leaks, 11% improper maint., 6% improper adjustment, 6% fuel flow incorrect
Main F/C & Pump	780/2640		
Sikorsky CH-53D 33,356 Flight Hours			
T64 Engine	375/814	46.5	20% improper adjustments, 10% FOD, 7% binding, 7% leaking
Main F/C	130/629	25.0	66% improper adjustments, 5% failed unk, 4% fuel leaks, 3% internal fail.
Pump	1235/5559	2.1	33% dirty, 15% fuel leaks, 11% missing parts, 7% improper adjustments
Main F/C & Pump			
<div> <div>T53-L-11 Fuel Control</div> <div>T53-L-13 " "</div> <div>T63 " "</div> <div>T58 " "</div> <div>T64 " "</div> </div> <div> <div>TA-2B, Chandler Evans</div> <div>TA-2S, Chandler Evans</div> <div>DP-D3, Bendix</div> <div>JFC26, Hamilton Standard</div> <div>JFC42, Hamilton Standard</div> </div>			

1. Different aircraft usage. Short-duration flights with many cycles of operation, compared to longer, steady cruises.
2. Different environments
3. Variation in maintenance personnel ability and reporting efficiency

It is also to be noted that the reliability of the engine reflects in the reliability of the control. A low MTBR for an engine will tend to increase the MTBR for the control. For example, a MTBR of 223 hours for the T58 engine on the Boeing CH-46D during 100,361 flight hours introduces 450 new engines and controls (100,361/223) compared to only 50 new engines and controls (21,500/428) for the T53 engine on the Bell AH-1G.

Considering the reporting system itself, the Navy's 3M data system represents what is typically available on the recording of fuel control R&M field data. The reporting of failures is limited to the selection of one- and two-word codes to define a cause for removal (81 out of 201 codes available apply to hydro-mechanical fuel controls). Also, causes of failure reported in the field are not verified. For this reason, many removals are reported as improper adjustments, and the emphasis for obtaining failure data in the program relied upon surveying users and fuel control overhaul facilities.

Table II shows a more detailed breakdown of the T53 control system faults. This data is the result of work done by Chandler Evans, initiated by Trouble Failure Reports (TFR's) covering the period January 1969 to January 1972.

Generic Failures

The most useful data for this part of the program came from verbal opinions taken in the survey. This resulted in the definition of the following generic failure modes:

TABLE II. TA-2 CONTROL UNSCHEDULED MAINTENANCE Period Covering 1/1/69 to 1/1/72		
Total Maintenance Actions		1392
Inconclusive (cause unknown)		<u>555</u>
Reported Actions		837
FAILURES NOT AFFECTING ENGINE PERFORMANCE (DIRECTLY)		
	Symptom	% of Confirmed Failures
	No Defect Found	20.0
	Leakage	18.5
	Wear	12.5
	Emergency System (backup)	<u>12.6</u>
	Total	63.6
FAILURES DIRECTLY AFFECTING ENGINE PERFORMANCE		
Order	Symptom	(%)
1	Accel. Fuel Flow High	6.0
2	Accel. Fuel Flow Low	9.0
3	Out of Adjustment (limits)	5.4
4	Incorrect Starting Fuel Flow	3.1
5	Inconclusive Symptoms	5.5
6	Loss of N ₂ Control Only	1.7
7	P ₃ Air Bleed Incorrect	<u>5.7</u>
	Total	36.4

1. Wear - major wear in drive splines and couplings;
minor wear in computing elements
2. Contamination of:
 - a. Air - with oil and atmospheric pollution in pneumatic systems
 - b. Fuel - contamination introduced into the aircraft fuel tanks and left in the fuel control during assembly
3. Incorrect Adjustments/Tampering With Adjustments
4. Seal Leakage - internal and external

The order of the magnitude of these problems as a percentage of confirmed fuel control failures is:

Wear	12%
Contamination	10%
Incorrect Adjustments	20%
Leakage	15%

These are the major problem areas which, if eliminated, would significantly improve the control system life. The remaining 43% are failures of a random nature; for example,

Human errors - incorrect assembly, maintenance, transportation, manufacture

Defective materials - porous castings, material flaws, cracks

Calibration errors - random cases where the control errors may be biased to one side coinciding with an engine whose performance is also biased

Incorrect control rigging

A specific requirement of the program was to investigate control faults previously experienced by the Army.

1. Sensors and compensating servos
2. Fuel contamination
3. Wear - computing elements
4. Wear - drive couplings
5. External leakage
6. Wear or failure of flexible drive shafts
7. Fracture or deformation of control attachment hardware
8. Lack of fault-isolation hardware
9. Other fuel control problems

Item 1 was not found to be a problem common to all controls in general, and will be discussed as a specific problem in the T53 control history.

Items 2, 3, 4 and 5 were confirmed as being failure mechanisms common to all controls.

Flexible drive shafts (Item 6) were confirmed to be a problem area. The main problem is excessive wear resulting in drive failure. A secondary problem is binding, which results in unstable power turbine speed.

Item 7 was not reported in the survey as being a problem area.

Fault isolation (Item 8) is discussed in the second section of this report.

The generic failures identified - wear, contamination, incorrect adjustments, and fuel leakage - were studied in detail with reference to the T53 engine control since this control represents 66% of the total gas turbine fuel controls in active Army service.

Detailed Study of Generic Failures (Applied to T53 Engine Control)

1. Wear

Wear is the general term for the complex phenomenon of deterioration of surfaces in use. It may be divided into more commonly understood types of wear as follows:

- a. Abrasion - The wear produced by the shearing action between surface irregularities or foreign particles in continuous motion.
- b. Adhesion (galling, scuffing, scoring, seizing) - The wear caused by welding of irregularities, resulting in local projections and cavities, which in turn can cause further damage.
- c. Fretting - Small reciprocating motion causing surface failure due to fatigue. This is often accompanied by corrosion because the wear removes the natural protection of corrosion on the surface and hence a cycle of wear-corrosion-wear is produced which removes material rapidly.
- d. Contact Stress Fatigue (Pitting) - The dynamic application of load which causes fatigue failure at the surface due to high-hertz stresses. The failures are seen as local pitting, and the loose particles may cause further damage by abrasion.
- e. Galvanic Corrosion - The electrical depositing of material due to dissimilar materials.

Temperature Effect

In addition to the above wear categories, the general effect of an increase in material temperature is to increase the wear rate by reducing the material hardness and corrosion resistance.

Drive Spline Wear

The area of wear which has the most serious effect on control systems is in drive splines. The wear is usually in the form of combinations of abrasion and fretting corrosion. Design guidelines are to minimize surface stresses and drive eccentricities and provide well-filtered liquid lubrication. The spline teeth should be of a hard material and be chromium plated to provide corrosion resistance and minimum friction. The purpose of providing liquid lubrication as compared to oil mist is to minimize corrosion in the area inaccessible to oil mist, where fretting corrosion would normally take place.

Areas of drive shaft wear on the T53 control are shown in Figure 7 for the main fuel control drive and in Figure 8 for the power turbine governor drive. The most severe wear area is the main drive spline (Item 1, Figure 9). Originally this spline was Nitralloy (AMS 6470) and was run dry. This resulted in a high frequency of worn splines. The shaft material was changed to Nitralloy AMS 6475 and was lubricated with oil mist.

The problem with Nitralloy is that the white layer (iron nitride) formed during nitriding causes the chromium plate to flake off, allowing fretting corrosion to take place. Complete removal of the white layer from a spline is difficult and cannot be successfully inspected.

This problem is illustrated in Figure 9. An example of a worn spline was sectioned and found to have 0.0004 inch of white layer with only particles of chromium remaining on the surface. The other example shows a drive shaft which had been used in the field and did not show signs of wear. This spline had no white layer and the chromium plate was still in place.

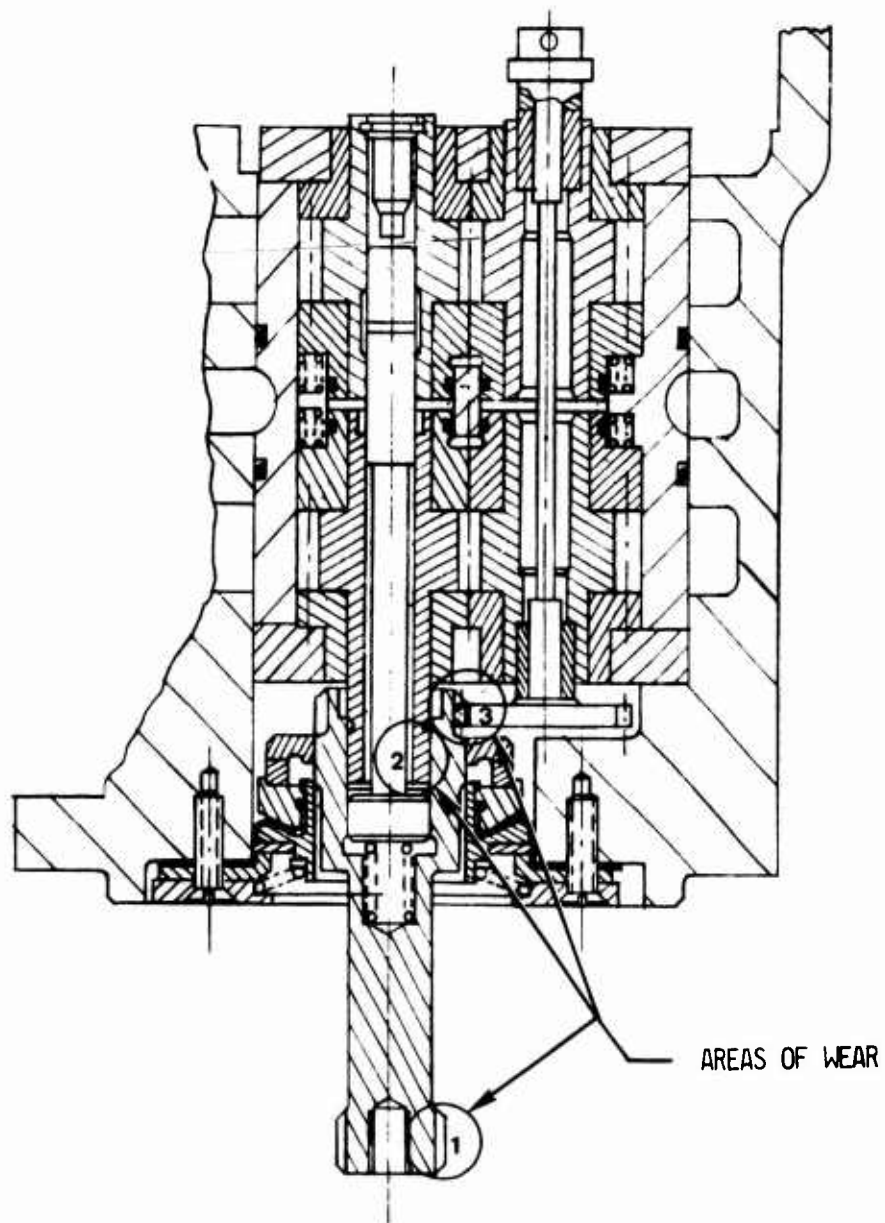


Figure 7. Main Fuel Control Drive.

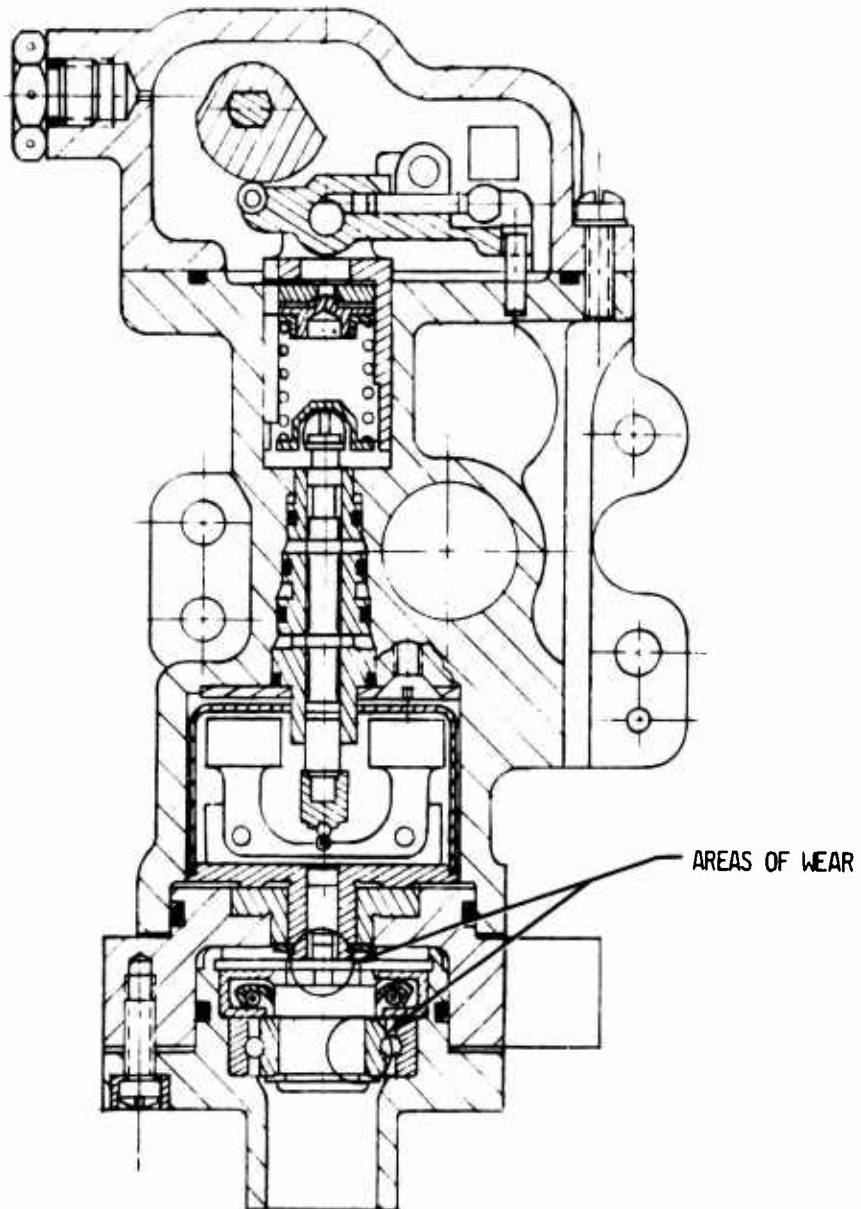


Figure 8. Power Turbine Governor Drive.

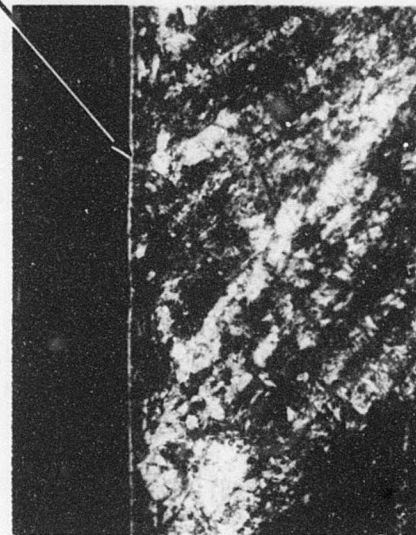
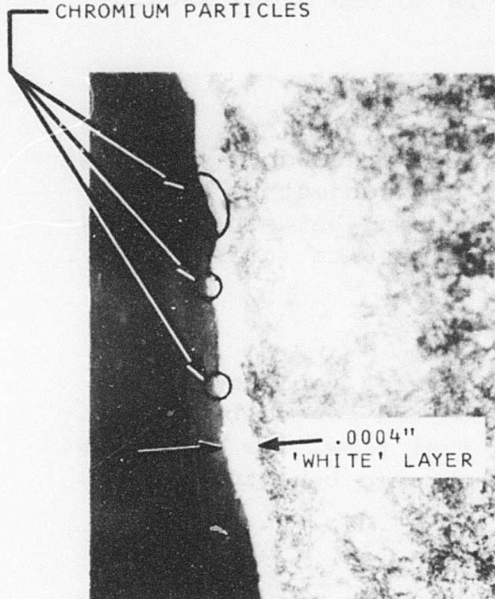
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MAGNIFICATION 500/1

CHROMIUM PARTICLES

CHROMIUM PLATE (NO WHITE LAYER)



WORN SPLINE FLANK

SURFACE HARDNESS - 15 N 93.5

CORE HARDNESS - R_C 42

NITRIDED CASE DEPTH - .017"

UNWORN SPLINE FLANK

SURFACE HARDNESS - 15 N 93

CORE HARDNESS - R_C 41

NITRIDED CASE DEPTH - .017"

AREA SHOWN MAGNIFIED



DIRECTION OF DRIVE

Figure 9. Spline Wear Problem.

It has been demonstrated by 150 hours of engine running at Avco Lycoming that a better solution to the drive spline wear problem is to use Greek Ascaloy (AMS 5616) chromium plate.

N_1 and N_2 Drive Coupling Wear

The N_1 and N_2 flyweight drives are Oldham couplings (N_2 shown in Figure 8) and are subject to high-frequency small-amplitude rubbing between the coupling drive's surfaces. This results in fretting.

2. Contamination

It is believed that many failures reported in the field as system faults are often caused by contamination; for example, high fuel flow, low fuel flow, out of specification, and erratic behavior.

Contamination of Air

Pneumatic controls are used in T63 and T74 engines. Flowing engine compressor air is used for computation and actuation power. This introduces oil and atmospheric contaminants into control orifices and check valves to the extent that they sometimes clog. The areas affected are the N_1 and N_2 governor orifices, acceleration orifice, orifices upstream of the governor and acceleration bellows, and two check valves used in dynamic compensation of the power turbine governor. The air cannot be filtered without sacrificing fuel control performance. The pressure drop across the filter introduces an error in fuel flow directly proportional to the filter pressure drop. The error will increase with additional time of operation.

Contamination of Fuel

Contamination of fuel has two effects: it limits the life of components by producing abrasive wear, and it degrades control and engine burner nozzle performance.

Currently the finest barrier filters commonly used are 10μ nominal ($1\mu = 0.000039$ inch) which gives an absolute rating of 25μ . Using MIL-E-8593B as the standard for contamination distribution, a 25μ absolute filter would allow 82% of the total contaminant weight to pass through to the fuel control and burner nozzles.

Much work on the contamination of hydraulic systems has been done, and experience indicates that the filtration rating provided must be less than the system clearances to minimize abrasive wear. Applying this criterion to gas turbine controls, a spool valve has a typical radial clearance of 0.00015 to .00025 inch or 4 to 6μ ; a system filter of 3μ absolute is therefore required.

A summary of the benefits to be gained from finer filtration is as follows:

- a. Longer life components, hence increased time between overhauls.
- b. Increased reliability, by the elimination of problems such as erratic behavior, stuck valves, etc.
- c. Minimized silting forces on servos, resulting from smaller controls.
- d. Reduced erosion of housings, orifices, burners.
- e. Better system performance (long-term accuracy and stability).

The penalty for these advantages is higher frequency of filter replacement, higher filter costs, and larger filters. For example, a barrier filter sized for the T53 engine would be 3 inches in diameter by 8 inches long, based on a fuel flow of 600 lb/hr, $\Delta p = 10$ psi and a filter life of 20 hours or 40 flights (fuel contaminated to MIL-E-8593B).

The following is a brief survey of applications of fine filters already in use:

<u>Engine Manufacturer</u>	<u>Engine</u>	<u>Application and Comments</u>
Lycoming	ATAGS-T55	3 μ absolute, on oil system
P&W	JT8D	Oil system filter, recently used
	TF30	Oil system filter (3-1/8" dia. x 6-1/2" long)
P&W	T74	3 μ absolute filter for filtering compressor air for the pneumatic fuel control system (1" dia x 2-1/4" long)
Williams	WR27 (APU)	3 μ absolute, on oil system
		3 μ absolute, on fuel system to eliminate sludge problem which 25 μ filter did not cure

3. Incorrect Adjustments/Tampering With Adjustments

It was reported during the survey of control system failure modes that incorrect adjustments and tampering with adjustments are major problems. However, the allowed field adjustments for the T53, T55, T63, T73 and T74, while affecting the engine performance, do not disturb the basic calibration of the fuel control. Adjustments which are critical to the calibration of the control usually have lead seals, and in some instances "torque paint" is used on joints and screws which shows cracking if these components are disturbed.

The problem could be reduced in magnitude if all external adjustments which are used for control

calibration were positioned so that when the control is mounted on the engine, the adjustments are inaccessible. For future controls, the only complete solution is to provide no adjustments.

4. Seal Leakage

The most important leakage problem is external fuel leaks from the pilot's input to the control. The leaks can be sufficiently high to be a safety hazard. The general requirements for this seal are:

Temperature range	-65° to 250°F (350°F for the future)
Pressure	usually relatively low, 200 to 300 psi
Velocity	usually low, typically 0.1 ft/sec
Cycles	for a 5000-hr TBO, 15,000 cycles of flight conditions or 100,000 cycles in laboratory conditions
Shelf life	no aging restrictions

There is no material currently available which meets all of these requirements. The following is a list of current materials and their weaknesses:

Buna N - meets the temperature range, pressure and velocity requirements. However, it tends to go brittle with time. The time that it takes to go brittle in the field varies from 100 hours to many thousands of hours depending on the environment. The material hardens both in fuel and in air.

Fluorocarbon - is brittle at low temperatures.

Fluorosilicone - has very poor wear resistance.

Polytetrafluoroethylene - flows under load, otherwise it satisfies all other requirements.

The results of this information indicate that new seal materials or improved seal designs are required. A preliminary survey of the commercial seal market indicates that new seal designs and materials have been recently introduced which offer the potential for solving the fuel leak problem.

The new materials include a new Buna N compound and Epichlorohydrin. Hydrin elastomers are reported to offer high resiliency and almost constant hardness over a wide temperature range with good low temperature properties. They are highly resistant to JP fuels and exhibit good aging and abrasion resistance.

The new designs combine the high wear resistance of polytetrafluoroethylene and the mechanical integrity of fluorosilicone or mechanical springs for structural support. Various configurations using these combinations of material are currently available. All of the configurations use the polytetrafluoroethylene for the dynamic seal.

These new materials and design configurations must be test evaluated to determine if they can operate in the specified environment and provide the required service life. Also, present seal material specifications should be reviewed to determine if more stringent control of the ingredients will enhance desirable seal properties.

It is recommended that a survey of seal manufacturers be made to review and evaluate the new designs and material combinations, and that the most promising designs be selected for bench test evaluation.

FAULT-ISOLATION DEVICE

A principal factor in the formation of maintenance policies is cost effectiveness; that is, within constraints, maintenance policies are based on achieving goals for the least expenditure of resources. This effort has been concerned with an analysis and evaluation of gas turbine fuel control fault-isolation devices and their potential impact on the life-cycle cost of the fuel control. Specifically, we will attempt to answer the following question based on available historical maintenance data:

"Can a device used for fault isolating the fuel control be cost effective when included as part of the U.S. Army aviation maintenance system?"

The study has been divided into the following three basic sections:

1. Functional Description of Fuel Control Models
2. Fault-Isolation Device Cost Goals
3. Fault-Isolation Techniques

The first section is concerned with a functional description of U.S. Army fuel control models and the basic requirements for fault isolation on each model.

The second section analyzes the life-cycle cost factors and computes the potential cost savings on those factors where a fault-isolation device (FID) has an impact on cost.

The third section describes various possible FIDs for both a current hydromechanical and an advanced electronic control. Based on cost effectiveness, a detailed design is made for the most promising FID for a hydromechanical control.

Functional Description of Fuel Control Models

Descriptions and functional schematics of the T53, T55, T63, T73 and T74 engine controls have been covered in the sections dealing with failure mode analysis. This section is concerned with the basic functional mechanization of these fuel controls and specifically notes the similarities and differences that may be significant in developing fault-isolation techniques. An advanced-electronic-technology fuel control design has been included in the comparison to indicate trends for future Army gas turbine engines. It consists of a hybrid electronic computing section; a hydromechanical fluid metering, fuel pumping, and alternator section; a variable inlet guide vane actuator; and the necessary transducers and sensors for signal sensing. This control design is based on an advanced engine control program conducted for the Eustis Directorate, USAAMRDL (Ref. 11).

Fuel Control Functional Block Diagrams

Figures 10 through 15 describe the functional mechanization of the fuel control models listed above in the form of block diagrams. Specifically indicated are:

Input/output parameters

Methods of signal transducing

Types of mechanisms used for computing
metering valve position

Pumping and fuel pressure regulation

Dynamic compensation

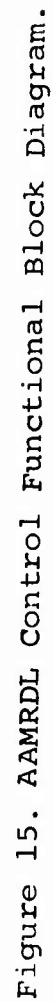
2D and 3D cams

Servo systems

Additional geometry control modes

These diagrams are not intended to be complete in every detail; in some cases, functions which are not directly relevant to fault isolation are ignored completely. The





basic features of these fuel control models are given in Table III and discussed below.

Basic Features

1. All controls meter the fuel flow on the basis of the orifice equation

$$W_f = KC_d A_R \sqrt{\Delta P}$$

where

K = constant

C_d = discharge coefficient

A_R = metering area

ΔP = pressure drop across metering area

All of the controls regulate the pressure (ΔP) across the orifice, and fuel flow is metered by varying the metering area. This is achieved on all controls by means of a metering valve. The valves differ only in their shape and stroking mechanisms.

2. All controls contain a computing section whose output controls the metering valve position according to preset limiting schedules (acceleration and deceleration) and speed governing requirements.
3. The mechanisms used for computation vary between control models. Of the turbine engine fuel controls presently in use by the Army, 80% are hydro-mechanical and 20% are pneumatic. The two pneumatic control models used are produced by the same manufacturer and use similar techniques throughout. The three hydromechanical fuel control models vary somewhat in mechanization of similar functions; for example, flapper valves versus spool valves. Because of the complexity of the computing mechanisms within the fuel controls, it is apparent that

TABLE III. U. S. ARMY ENGINE SELECTED FUEL CONTROL FEATURES

Engine Designation	T53	T55	T63	T74	T73	Future	Notes
Fuel Control Designation	TA-2	JFC-31	DP-D3	DP-F2	JFC-56	AMRDL Control	
Manufacturer	Chandler Evans	Hamilton Std	Bendix	Bendix	Hamilton Std	Chandler Evans	
Type	Hydromechanical	Hydromechanical	PN/Mechanical	PN/Mechanical	Hydromechanical	Electro/H/Mech.	
Pump	Included in Unit	Yes	Yes	No	Yes	Yes	
	Single-Element Gear	-	-	No	-	-	
	Dual-Element Gear	X	X	X	X	X	
	Centrifugal	-	-	-	-	-	
	Inlet Filtration	Yes	Yes	Yes	Yes	Bocast Only	X
	Filter Bypass Warning	No	No	No	Yes	Yes	No
	Pump Speed (1000 RPM)	4.8	Std	4.5	4.5	4.25	No
	Main Pressure Regulator	Std	Std	Std	Std	Servo assisted	Std
	Main Regulator DP	20	40	-	-	-	-
	Manual Adjustment	Yes	Yes	Yes	Yes	Yes	Yes
Main Metering System	Fuel Type Adjustment	Yes	Yes	Yes	Yes	Yes	Yes
	Temp. Compensation (Fuel)	No	No	No	Yes	Yes	Yes
	Metering Valve Type	Cylindrical Contoured Spool	Window With Axial Plunger	Contoured Needle in Orifice	Contoured Needle in Orifice	Window With Axial Plunger	Swept Contoured Window
	Metering Valve Drive	Axial Hydr. Force Against Spring	Hydraulic Force Feedback	Pneumatic Bellows	Pneumatic Bellows Force	Hydraulic Force Feedback	Electric Stepper Motor
	Metering Valve Operation	$\sqrt{W_p/P_2}$ provides radial force onto tangent sliding $\sqrt{P_2}$ arm. Moves longitud. M. valve	Longitudinal motion of W_p/P_3 against a tangential P_3 mult lever moves lateral plunger	Movement of bellows trans to cross shaft and associated levers	Same as T63	Force balance W_p/P_3 positions force point. P_3 supplies prop force servo feedback thru M. valve	Electronic computer controls stepper motor in proportion to required W_p
	N ₁ Speed Sensor	Flyweight	Flyweight	Flyweight	Flyweight	Flyweight	Magnetic pickup
	N ₂ Speed Sensor	-	-	-	-	-	-
	P ₂ Pressure Sensor	Bellows	-	-	-	-	-
	P ₃ Pressure Sensor	-	Bellows	Pneumatic Pressure	Pneumatic Pressure	Bellows (2)	Diaphragm Capacitance
	T ₂ Temperature Sensor	Fluid expansion into bellows	Liquid-filled bellows	-	Bi-metallic	-	Thermistor network
Sensors	T ₄ (Turbine Inlet)	-	-	-	-	-	-
	T _{5B} (Turbine Blade)	-	-	-	-	-	-
	T ₅ (Exhaust Temp.)	-	-	-	-	-	Pyrometer (Radiation)
	P ₁ (A/R Bleed)	External Unit	External Unit	-	-	External Unit	-
	Accel/Decel Control	Std 3D Cam $\sqrt{W_p/P_2} \cdot F(N_1, T_2)$	Std 3D Cam $W_p/P_3 \cdot F(N_1, T_2)$	Pneumatic Bellows with Enrichment Section	As for T63	2D Cam $W_p/P_3 \cdot F(N_1)$	Electronic Function Generator $W_p/P_3 \cdot F(N_1, T_2)$
	N ₁ Governor Control	Prop W_p/P_2 with N ₁ T ₂ compensation	Prop flyweight servo system with droop compensation	Pneumatic bellows against accel. bellows	As for T63	Proportional W_p/P_3 with N ₁ & P ₂ droop compensation	Electronic fixed prop gain
	PLA Input	Input thru 2D cam with adjustments	2D cam with adjustments	2D cam, idle and max adjustment only	2D cam with idle max adjustments	Input thru 2D cam with adjustments	Resolver angular input from mech. cam link
Computer Section	N ₂ Governor Control	$\sqrt{W_p/P_2}$ prop to N_2 error thru low-wins linkage	75-100% W_p/P_3 prop to N ₂ error	94-105% pneumatic with lag and deadband	Propeller governor	Proportional W_p/P_3 mode with C/P reset	Electronic isochronous with dynamic compensation resets N ₁ governor
	W _p /P x P Multiplier	Approximates $\sqrt{P_2}$ mult.	P ₃ tang multiplier	Pneumatic bellows	As for T63	P ₃ tangential multiplier	P ₃ multiplier done electronically
	Collective Pitch Reset	Stick resets N ₂ governor	Through N ₂ lever	Collective stick resets N ₂ governor	Not Applicable	N ₂ selector cross coupled to lever	Potentiometer input to electronics
	Other Functions	3D cam includes 1GV & P ₃ bleed control	3D cam includes P ₃ bleed control	None	None	2D cam includes P ₃ bleed control	1GV 3D schedule in electronics
	Compressor Bleed Control	X	X	-	-	X	- (X)
	Variable Geometry	X	-	-	-	-	X
	Emergency System	X	-	-	-	-	X
	Scrub Valve (Sitting)	-	X	-	-	-	-

simple fault-isolation signatures will not be identified. A fault-isolation device must, therefore, be based on the functional performance of the fuel control computer. This may be done by measuring the metering valve position (or, alternatively, measuring the actual fuel flow) and comparing it to the correct position computed by a fault-isolation device.

4. The pressure drop across the main metering valve is a unique failure signature for the fuel metering sections of all control models. All failures in the fluid controller which cause the engine to malfunction will be manifested in this pressure measurement. This covers faults in the boost and main fuel pumps, the main pressure regulating valve, malfunctions in check and bypass relief valves, and gross internal leakage due to seal deterioration. However, maintenance data indicates that these sections of the fuel control unit may account for, at the most, only 20 to 30% of the total failures. Therefore, it is apparent that a fault-isolation device based on this parameter could be effective only if combined with a device that will fault-isolate the fuel control computer.
5. Mass-fuel-flow sensing devices are not included in the majority of present-day U.S. Army aircraft. Also, the next generation of Army helicopters represented by the UTTAS program are not providing these devices as part of the aircraft system. It follows that fault-isolation concepts based on fuel-flow measurement must include the fuel-flow measuring device as part of the system cost. A survey of mass-fuel-flow sensors indicated that the price of these devices would probably be prohibitive for this application. This would tend to favor schemes based on two separate performance measurements, these being:

- Metering valve position
- Fuel pressure drop across the metering valve (ΔP)

6. Fuel-control models vary in their requirements for geometry control of the inlet guide vanes and compressor bleed. For the T63, neither function is provided in the fuel control, while on the T53, both are provided. For control systems that include either of these functions, a fault-isolation device must account for them independently. Each geometry control is an independent fuel control output that must be given an independent performance test for fault isolation. The control model used as the reference for trade-off studies includes an inlet guide vane control.
7. With one exception, all fuel control models use compressor discharge pressure (P_3) as an input control parameter. The exception is the T53 engine fuel control, which senses compressor inlet pressure (P_2). For built-in fault isolation, the requirements would be basically the same for P_2 or P_3 . However, for ground test equipment, measuring P_3 would still require a pressure sensor to be built in to the fuel control unit or to make a connection to the engine. The P_2 measurement could be made by using a ground-based atmospheric pressure sensor. This would allow the cost of the sensor to be shared among several aircraft.
8. All of the hydromechanical fuel controls use 3D cams for scheduling fuel flow, inlet guide vane position, and compressor bleed. The pneumatic controls are used on smaller engines with less stringent control requirements. This is reflected in their simpler scheduling systems with a resulting lower unit cost. It can be assumed, therefore, that the fault-isolation device required will be of a complexity proportional to the particular control model.

Metering Head Pressure Fault-Isolation Systems

The constant metering head pressure system is common to all of the fuel control models considered; therefore, use of the metering valve differential pressure (ΔP) to identify malfunctions in the controller has been treated separately.

In general, the main pressure regulating valve maintains a constant pressure differential across the metering valve by bypassing excess fuel to the pump inlet. Maintaining a constant pressure differential makes metered flow proportional to the area of the main metering valve.

Figure 16 shows a functional block diagram of a ΔP fault detection mechanism. A differential pressure sensor measures the pressure across the fuel-metering valve and compares it to a set reference. If they do not agree within the allowable error band, a NO-GO is indicated at the fault-isolation device readout. It is significant that the required pressure monitoring ports are on all presently used fuel controls, as these points are required for bench calibration and setup of the control.

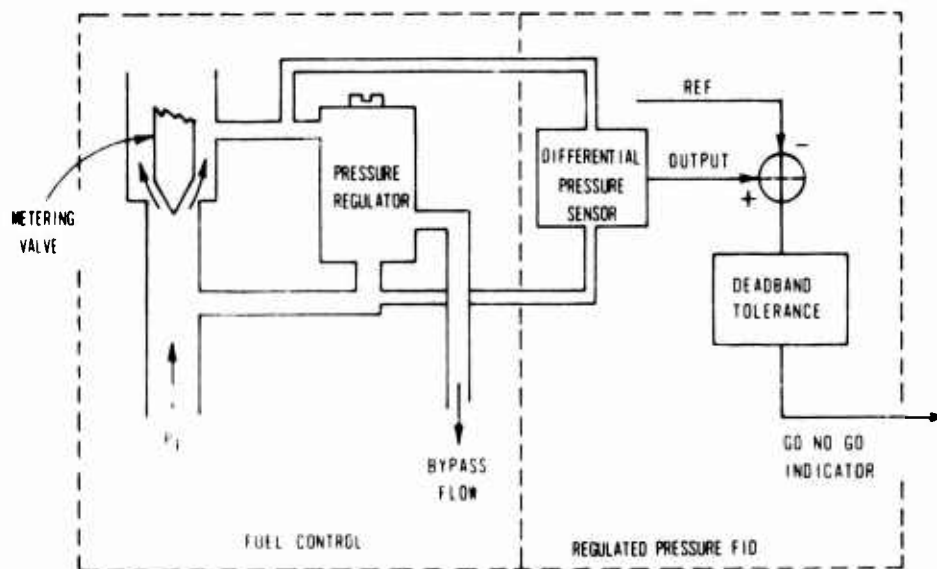


Figure 16. Metering Valve Pressure FID Block Diagram.

For future controls, the ΔP failure sensor could be included as part of the control at a marginal increase in complexity and cost. Such a system may consist of supplying an electrical ground signal to the control FID monitoring connector if a bellows sensing ΔP is displaced outside the acceptable limits. Figure 17 indicates such a scheme. Also, hydromechanical designs could be provided which would cause a flag to pop up.

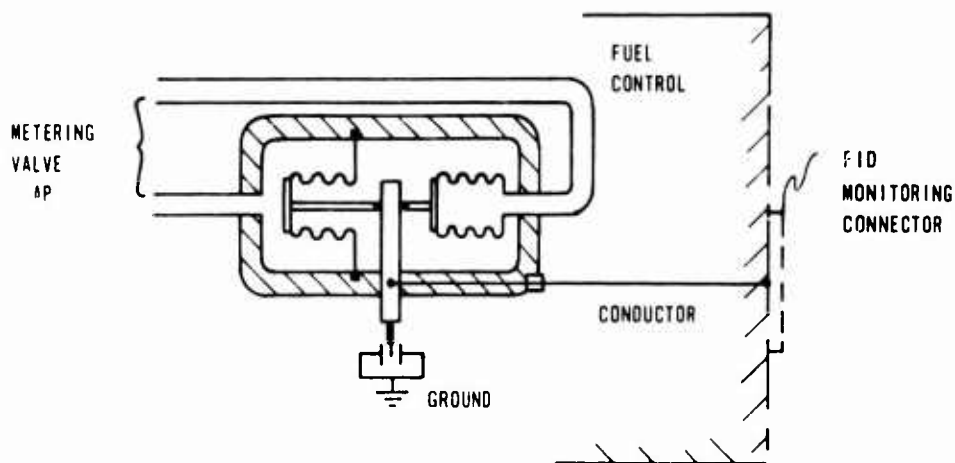


Figure 17. Metering Valve Differential Pressure Sensor.

Fault-Isolation Device Cost Goals

This section is devoted to an investigation and analysis of U.S. Army gas turbine fuel control life-cycle cost savings which could result from the effective use of a fuel control fault-isolation device (FID). In particular, an effective FID will eliminate the present high incidence of unjustified removal of fuel controls from Army aircraft. The cumulative cost savings associated with the elimination of these unjustified removals will be used as a goal for cost effectiveness in evaluating and selecting potential fault-isolation schemes.

By analyzing ownership costs associated with the fuel control over the average operational life of the aircraft, an indication of areas where costs may be significantly reduced by an FID should be apparent. However, detailed information was not available on all of the pertinent life-cycle cost items being considered, and in these cases it was necessary to make cost estimates.

The results of the cost analysis are summarized in Table IV, which lists the estimated cost savings offered by a 100% effective FID for each of the life-cycle items considered in the analysis. A 10-year life cycle of 500 flight hours per year for a total life cycle of 5000 hours was assumed.

The cost analysis computed potential savings considering unjustified removal rates of 25, 35 and 50%. Costs were determined as a function of the production price of the control. Figure 18 shows the results of this analysis and indicates the maximum allowable cost of the FID as a function of percentage of unjustified removals for fuel control production prices between \$2000 and \$20,000. The normal cost goal is indicated at the 35% unjustified removal level, which (based on Army experience) is the average unjustified removal rate.

The actual allowable cost of the FID will depend on the effectiveness of the FID. A 100% effective FID would always correctly indicate when a control removal was warranted. Conversely, a 65% effective FID would result in 35% of the removals being unjustified. This situation duplicates the present nominal unjustified removal rate, so theoretically a 65% effective FID could not be cost effective. Assuming a linear relationship between the cost of the FID and its effectiveness

TABLE IV. COST SAVINGS PER 1000 FLIGHT HOURS ACCREDITED TO THE ELIMINATION OF UNJUSTIFIED FUEL CONTROL REMOVALS					
Life-Cycle Costs	Percent Unjustified Fuel Control Removals			Remarks	
	25%	35%	50%		
1 Development and Production	\$ 0.00	\$ 0.00	\$ 0.00	FDI will not impact on these costs.	
2 Test Equipment	0.00	0.00	0.00	Assumes facilities and test equipment savings will be offset by requirements for maintaining the fault-isolation device.	
3 Facilities	0.00	0.00	0.00		
4 a) Maintenance Manpower (Organizational level)	13.35	18.70	26.70		
b) Maintenance Manpower (Intermediate level)	56.50	79.00	113.00	Not dependent on the unit cost of the fuel control.	
5 a) Fuel Control Stock Spares	28.75 C/L	40.25 C/L	57.50 C/L	Stock level reduction proportional to unjustified removal percentage.	
b) Fuel Control Pipeline Spares	10.30 C/L	14.40 C/L	20.60 C/L	Pipeline spares reduction proportional to unjustified removal percentage.	
6 Logistic Support	0.00	0.00	0.00	Assumes no change in logistic support.	
7 Spare Parts	0.00	0.00	0.00	Unjustified removals will not be repaired.	
8 Overhauls	1.15 C/L	1.65 C/L	2.30 C/L	Overhauls resulting from unjustified removals with hightime.	
9 Reorder Costs	0.00	0.00	0.00	No change in reorder frequency.	
10 Supply Administration	0.00	0.00	0.00	Administrative costs for FDI will offset other gains.	
11 Transportation & Handling	10.00	14.00	20.00	Assumes average packaging and shipping rate of \$0.73 per pound per trip.	
12 Salvage Credit	0.00	0.00	0.00	Fuel controls have no salvage worth.	
13 a) Aircraft availability	0.00	0.00	0.00	FDI will not impact directly on aircraft operations.	
b) Accidents & Aborted Missions	0.00	0.00	0.00		
TOTAL	\$0.008C + 79.85	\$0.01126C + 111.70	\$0.015C + 159.70	Assumes a life cycle of 5000 flight hours.	
C = Unit cost of fuel control L = Life cycle in flight hours of operation					

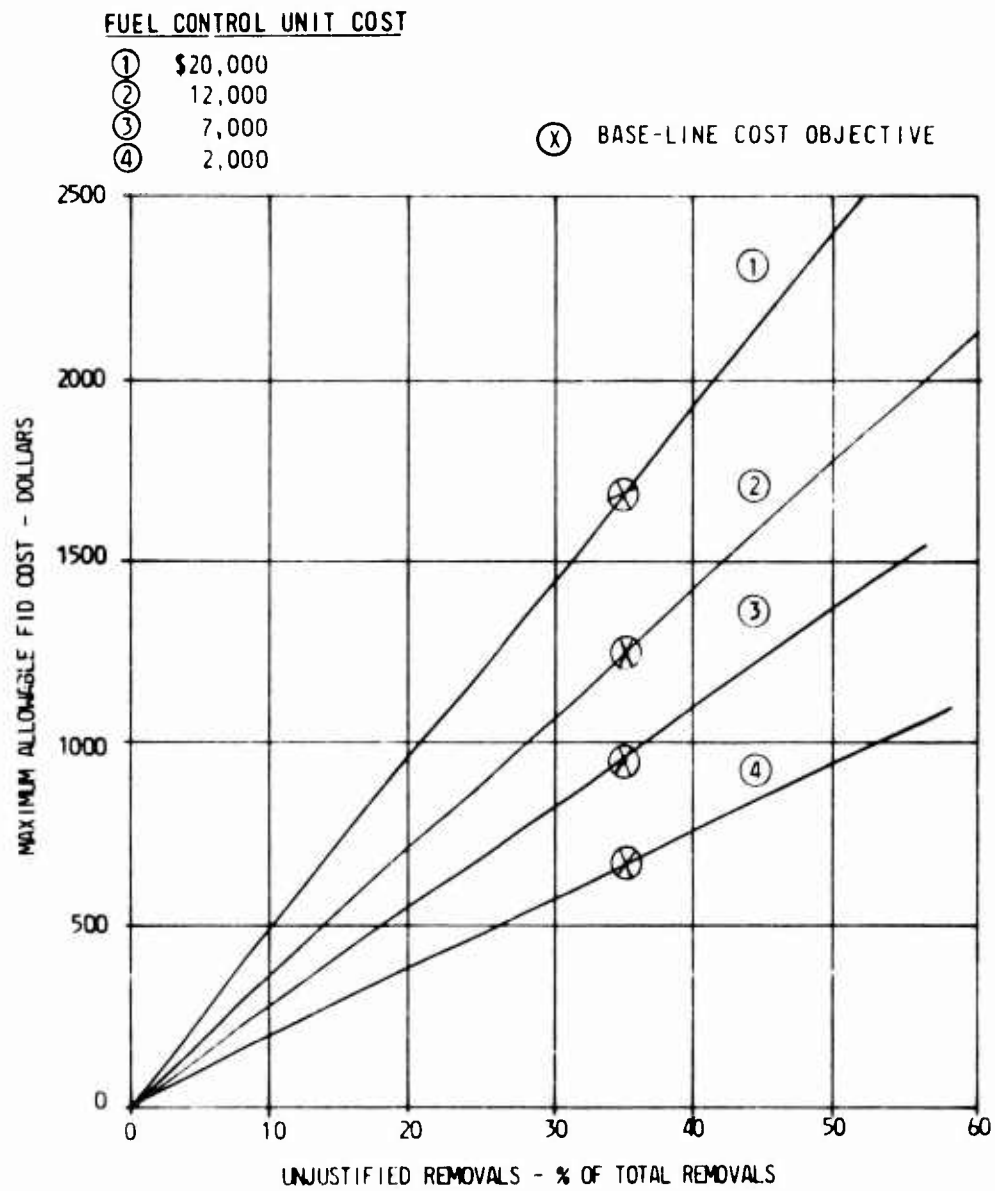


Figure 18. Fault-Isolation Device Cost Objective.

as indicated in Figure 19, and based on providing a realistic FID effectiveness between 90 and 95%, the corresponding FID cost goal is between 10 and 11.5% of the fuel control production price. The lower cost goal of 10% will be used for cost effectiveness even though it is anticipated that an FID effectiveness of greater than 90% will be achieved.

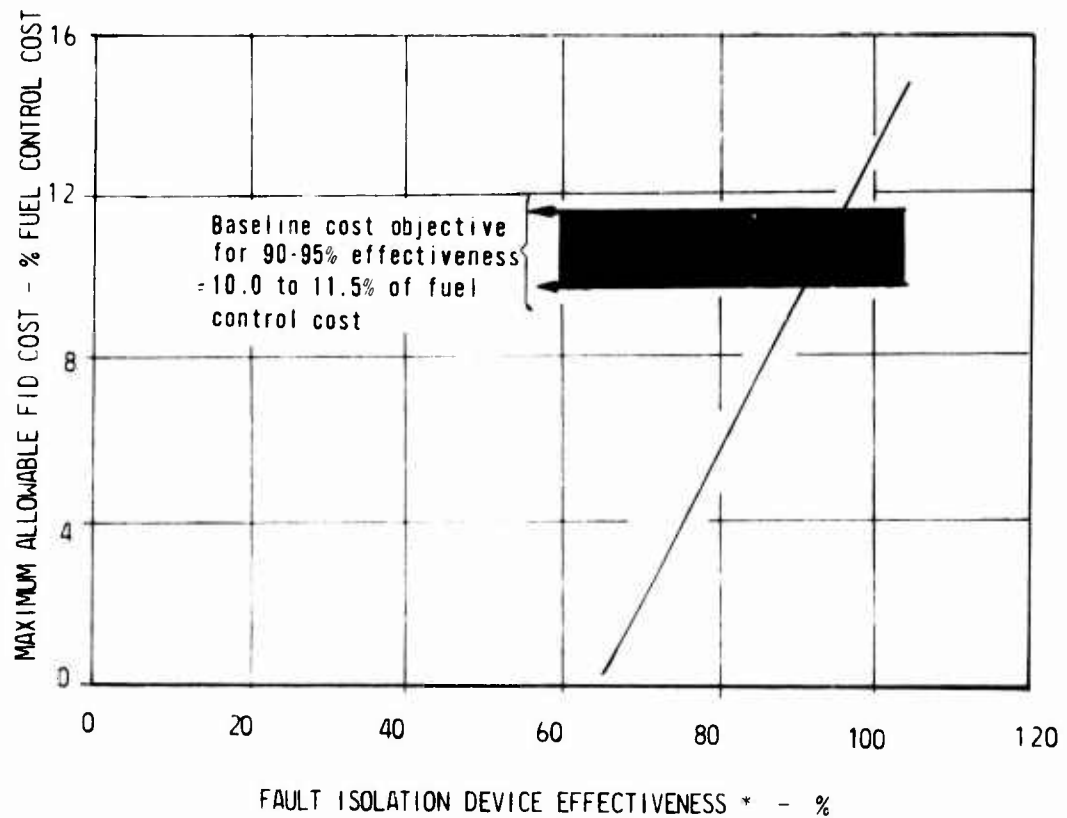
A discussion of each of the life-cycle cost factors and the cost computations summarized above are outlined in the following sections.

Maintenance Model

It could well be argued that what is cost effective for one specific aircraft fleet maintenance environment is not necessarily so for another. For example, tactical and utility helicopters in the wartime environment of the Republic of Viet Nam have created a maintenance picture completely different from that of fleets based in the U.S. in a peacetime environment. In a wartime environment, availability requirements will be at a premium, and hasty troubleshooting will probably cause a higher percentage of unjustified fuel control removals than would occur under peacetime conditions. Also, cannibalization will occur in remote front-line conditions in order to bring an aircraft on-line. To analyze all of the possible maintenance environments would not be practicable, and this study has considered the structure only as it is typically reflected in the maintenance history of present operational fuel controls. Cost effectiveness is based on these conditions' continuing to exist over the life-cycle period considered.

The fleet representation used in this cost study is based on UH-1 and AH-1 series helicopters which use the Chandler Evans TA-2 series fuel control (66% of Army gas turbine fuel controls). The operating theater is Southeast Asia, and a wartime environment is assumed. This is significant in estimating the fuel control repair/overhaul turnaround time. In a peacetime environment in which the majority of the aircraft fleets may be based in CONUS, turnaround times would obviously be reduced, requiring fewer pipeline spares, and therefore an FID would impact less. In general, all U.S. Army helicopter fuel controls follow similar maintenance procedures and practices, so it should be reasonable

BASED ON FUEL CONTROL HISTORY IN WHICH
35% OF REMOVALS WERE UNJUSTIFIED



*Effectiveness is defined as the percentage of the time the FID correctly indicated the go/no-go status of the fuel control

Figure 19. Current Hydromechanical Fuel Control FID Cost Objective.

to assume that the cost estimates derived (normalized with respect to the unit price) will be applicable to any of the fuel control models considered in this study.

The logistics and maintenance support system is based on a simplified picture of a base workshop supporting the various field organizational levels within the Southeast Asian operating area, while minor and major overhauls and redistribution are handled at a CONUS-based depot and the fuel control manufacturing plant.

Life-Cycle Cost Items

The following sections discuss the life-cycle cost factors which were considered in determining the potential savings offered by a 100% effective fuel control system FID. The methods used to compute the savings on those cost factors which are affected by an FID are also included.

1. Development and Production

These nonrecurring costs are reflected in the unit cost of the fuel control. They are usually well defined but can vary from year to year according to material and manpower cost escalations and production rate requirements. The unit cost of a fuel control as used in this study is averaged over the 10-year life-cycle period.

Although FID cost has been calculated as a percentage of the fuel control unit cost based on current cost estimates, the results should also be valid when applied to imminent and future projects, assuming that inflation will affect all areas of maintenance and production costs equally.

An FID, as will be shown in the following sections, could reduce the number of fuel controls required to support aircraft fleets by up to 10.2%. The resulting reduction in production rate requirements could result in some increase in the unit cost of the fuel control. However, for large production controls, this increase would be small if, in fact, it occurred at all, and therefore development and production costs would not be affected by an FID.

2. Test Equipment

This area of cost covers all equipment required for testing fuel controls. This includes equipment at both organizational and depot levels and includes such things as calibration test stands, special tools, test fittings, etc. The 10.2% reduction in the number of production controls alluded to above should result in a corresponding reduction in test equipment required to support the fuel control. However, in consideration of the complexity of an FID and its test equipment requirements, it is estimated that there would be no significant change in the overall cost of test equipment.

3. Facilities

Facilities for all facets of maintenance such as test, administration, logistics, stores, etc., are nonrecurring costs which would not be significantly impacted by the use of an FID. This assumes that any reduction in facility space arising from the reduced fuel control removal rate would probably be offset by the requirements for maintaining the FID. As a first approximation, and in consideration of the FID complexity, this assumption appears reasonable.

4. Manpower

The manpower requirements to support a maintenance policy will vary according to the scheduled and unscheduled maintenance tasks required. In both cases, this depends upon the reliability of the equipment and the efficiency of troubleshooting for fault-identification. As a result of fewer maintenance actions, the manpower requirements can be reduced. In this case, the man-hours saved will be the difference between the time required to set up and test the fuel control with the FID and the time to remove and replace the fuel control and determine if the malfunction has been

eliminated. This is based on the assumption that the FID is 100% effective and therefore all unjustified removals are eliminated.

Fuel controls unjustifiably removed from aircraft will not only consume man-hours at the organizational level but also at an intermediate level where the control is required to be bench tested. At this level, Government civilian personnel in wage grade 8 (WG-8) are used and man-hour costs are higher than for organizational level maintenance personnel (military grade E5).

Other manpower attributed to the handling and transportation of fuel controls is covered under those headings.

a. Organizational Level

Grade E5 maintenance personnel are used at this level. The cost, based on Army data, is \$9.50 per maintenance man-hour, which covers amortizing the cost of training, salary, hospital and welfare benefits, overhead, etc., over a productive year of 1000 man-hours.

From the analysis of available maintenance data (Reference 19), the following figures have been chosen as being representative of U.S. Army gas turbine fuel controls.

Mean time between removals = 400 hours

Average maintenance time
per removal = 3 man-hours

It is estimated that a fault-isolation device will reduce the average maintenance time spent on unjust removals to 0.75 hour. This gives a net savings of 2.25 man-hours for every unjust removal eliminated.

Cost Savings (Cs) (per fuel control unit per 1000 flight hours)

1. 50% of removals unjustified

$$\begin{aligned} Cs &= \frac{1000 \text{ hours}}{400 \text{ hours/removal}} \times 0.5 \text{ unjust} \\ &\quad \text{removals/removal} \times 2.25 \text{ man-hours /} \\ &\quad \text{unjust removal} \times \$9.50/\text{man-hours} = \\ &\quad \$26.70 \end{aligned}$$

2. 35% of removals unjustified

$$Cs = \$26.70 \times \frac{35\%}{50\%} = \$18.70$$

3. 25% of removals unjustified

$$Cs = \$26.70 \times \frac{25\%}{50\%} = \$13.25$$

b. Intermediate and Depot Level

Government civilian personnel in wage grade 8 are used at this skill level. The cost is \$12.87 per maintenance man-hour on the same basis as given in the organizational level manpower costs.

The man-hours attributed to a fuel control bench test vary considerably and, contrary to what might be expected, show no direct relationship to the unit cost of the fuel control. Of the fuel controls analyzed, the figures varied from 4 to 10 hours, and this study has assumed a mean time of 7 man-hours required for a fuel control to be checked out on a fuel test stand.

Cost Savings (Cs) (per fuel control per 1000
flight hours)

1. 50% of removals unjustified

$$\begin{aligned} \text{Cs} &= \frac{1000 \text{ hours}}{400 \text{ hours/removal}} \times 0.5 \text{ unjust} \\ &\quad \text{removals/removal} \times 7 \text{ man-hours/} \\ &\quad \text{removal} \times \$12.87/\text{man-hours} = \$113.00 \end{aligned}$$

2. 35% of removals unjustified

$$\text{Cs} = \$113.00 \times \frac{35\%}{50\%} = \$79.00$$

3. 25% of removals unjustified

$$\text{Cs} = \$113.00 \times \frac{25\%}{50\%} = \$56.50$$

5. Fuel Control Unit

The development and production costs of fuel controls required for the aircraft fleets were previously discussed, and an FID does not impact this cost. However, the total number of fuel controls required to support maintenance will be reduced by the effective use of an FID. These fuel controls are required in the following categories:

- a. Fuel controls used as spares to support field maintenance (held in stores).
- b. Fuel controls used to support the maintenance repair/overhaul pipeline to ensure that delays in the pipeline are compensated for (turnaround time).
- c. Fuel controls for spare engines.
- d. Fuel controls used to replace nonrepairable or lost controls (aircraft damaged or destroyed in battle).

Items (c) and (d) will not be influenced by the use of an FID, but requirements for spares needed for field maintenance and pipeline backup can be expected to diminish significantly. In the case of the pipeline backup spares, the reduction will simply be the total number previously required to maintain the turnaround time of the unjustified removals. The requirement for spares held in stores can be expected to drop by the same percentage as the reduction in fuel control removals.

a. Stock Level

The spares held in stock are approximately 20% of the number of aircraft in the fleet. It is assumed that these maintenance support spares could be reduced in proportion to the reduction in removal rate. Counting all fuel controls, the ratio of fuel controls in the Army inventory relative to the number of aircraft has been estimated at approximately 1.75.

Therefore:

$$\frac{\text{Stock Spare Units}}{\text{Total No. Units}} = \frac{20}{175} = 11.5\%$$

For

1. Unjustified removals = 50% of total

$$\begin{aligned} Cs &= \frac{11.5\%}{100\%} \times \frac{50\%}{100\%} \times \frac{C}{L} \times 1000 \text{ hours} \\ &= \$57.50 \frac{C}{L} \end{aligned}$$

where

C = unit cost of fuel control
L = life cycle in flight hours

2. Unjustified removals = 35% of total

$$Cs = \$57.50 \frac{C}{L} \times \frac{35\%}{50\%} = \$40.25 \frac{C}{L}$$

3. Unjustified removals = 25% of total

$$Cs = \$57.50 \times \frac{C}{L} \times \frac{25\%}{50\%} = \$28.75 \frac{C}{L}$$

b. Maintenance Pipeline Spares Requirement

Figure 20 gives a simplified picture of a typical fleet maintenance structure from field organization through to depot repair/overhaul. The transit times are representative estimates of times being experienced with present combat operations in the Republic of Viet Nam. This includes typical delays due to priority shipping, handling, rerouting, etc. Additional spares must be held which will allow for the transit time delays in the maintenance pipeline and ensure a continued supply of available spares at the fleet level. Summarizing these requirements, we have:

27% of the removed controls require 0.78 year turnaround.

Therefore:

$$\begin{aligned} \text{Required spares} &= 27\%/\text{year} \times 0.78 \text{ year} \\ &= 21\% \end{aligned}$$

27% of the removed controls require 0.545 year turnaround.

Therefore:

$$\begin{aligned} \text{Required spares} &= 27\%/\text{year} \times 0.545 \text{ year} \\ &= 14.5\% \end{aligned}$$

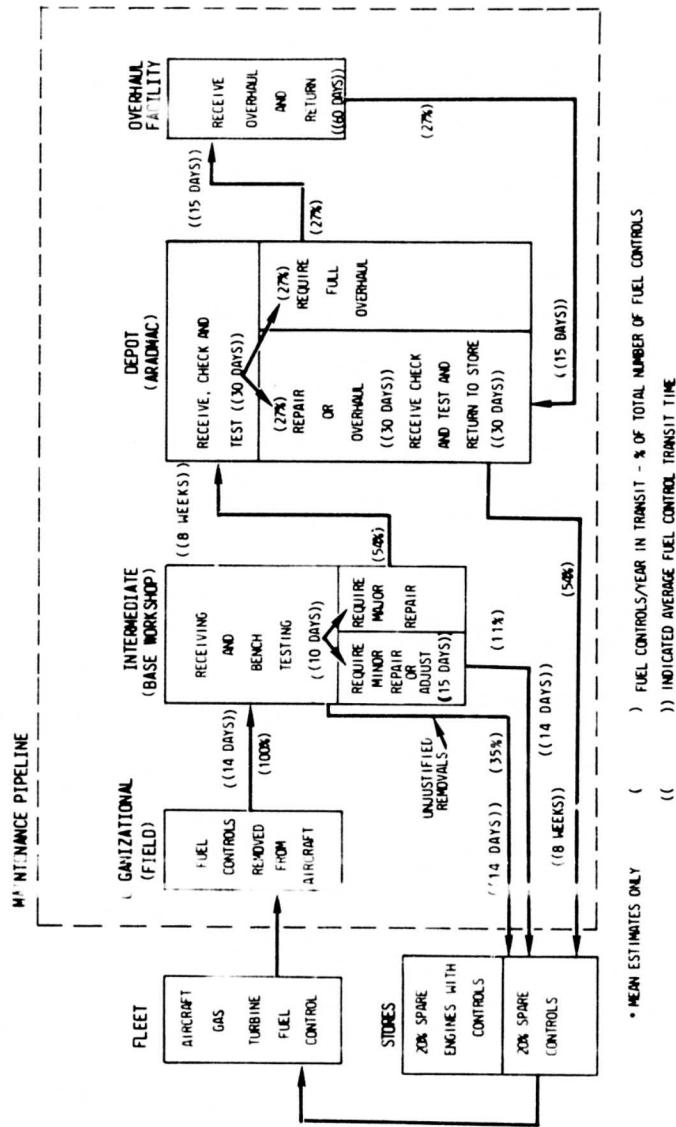


Figure 20. Typical U.S. Army Maintenance Pipeline.

11% of the removed controls require 0.145 year turnaround.

Therefore:

$$\begin{aligned}\text{Required spares} &= 11\%/\text{year} \times 0.145 \text{ year} \\ &= 1.6\%\end{aligned}$$

Unjustified controls removed require 0.104 year turnaround.

Therefore, required number of spares for:

1. 50% unjustified removals = 3.6%
2. 35% unjustified removals = 2.5%
3. 25% unjustified removals = 1.8%

The cost savings that may be realized is acquired by amortizing the cost of the spares that support this maintenance pipeline over the life cycle of the control.

The approximate index of fuel controls/ aircraft = 1.75.

Therefore, cost Cs is:

1. Unjustified removals = 50% of total

$$Cs = \frac{3.6\%}{175\%} \times \frac{C}{L} \times 1000 \text{ hours} = \$20.60 \frac{C}{L}$$

2. Unjustified removal = 35% of total

$$Cs = \frac{2.5\%}{175\%} \times \frac{C}{L} \times 1000 \text{ hours} = \$14.40 \frac{C}{L}$$

3. Unjustified removals = 25% of total

$$Cs = \frac{1.8\%}{175\%} \times \frac{C}{L} \times 1000 \text{ hours} = \$10.30 \frac{C}{L}$$

6. Logistic Support

This includes all utilities, etc., which are recurring costs established at the induction of the maintenance program. No change in these costs should be apparent as the result of a fault-isolation device used for fuel control maintenance.

7. Spare Parts

Fuel control parts used for repair and overhaul at intermediate and depot levels are recurring costs that depend on the reliability and the cost of the individual fuel control parts. However, by definition, this study addresses the unjustified removals which will not have parts replaced and, hence, will not be impacted by an FID.

8. Overhauls

Normally, overhauls are recurring maintenance costs that depend on either the degree of repair required (unscheduled) or the number of flight hours accumulated since the last overhaul (scheduled).

The maintenance decisions concerning fuel control overhauls vary from one fuel control model to another and depend upon their historic reliability performances. This study has considered the Chandler Evans TA-2S model as typical of the matured culmination of a fuel control series evolution. This should be more representative of the higher reliability expected from the next generation of fuel controls with scheduled overhauls of 5000 hours or more.

Although the total inventory of fuel controls can be reduced by the use of an FID, this lesser total would be required to accumulate the same total flight hours, requiring each control to be overhauled more often (calendar). However, the result will be the same total number of overhauls for the

life cycle of the aircraft fleet with no change in the total cost of fuel control overhauls. One side effect of an FID is the overhauls that would have occurred because controls were unjustifiably removed and had operated for more than 1800 flight hours (TA-2S scheduled overhaul). Analysis of maintenance data shows that on the average, these controls would have accumulated 300 more flight hours before being legitimately removed and sent for overhaul. Over the life cycle of the control, these overhauls can be used as a cost savings attributed to eliminating the unjustified removals.

The available maintenance history shows that on the average, 30% of removed fuel controls are overhauled. Of these 30%, 4.2% reached their scheduled overhaul high time and were therefore overhauled without a prior fault diagnosis. This includes controls that were unjustifiably removed. By analyzing the maintenance history of fuel controls with more than the scheduled overhaul time, it was estimated that they would operate, on the average, an additional 300 flight hours before being justifiably removed and overhauled. Over the life cycle of the control, there is some penalty in additional overhauls that can be used as a cost savings with an FID.

For the TA-2S fuel control, high time for overhauls = 1800 hours.

The mean time since last overhaul = 2000 hours.

With an FID, the expected mean time since last overhaul = 2300 hours.

Also, the approximate cost of an overhaul = $\frac{C}{3}$.

1. Unjustified removals = 50% of total

$$Cs = 4.2\% \times 50\% \times \frac{C}{3L} \left(\frac{1}{2000} - \frac{1}{2300} \right) \times 1000$$

$$\text{hours} = \$2.30 \frac{C}{L}$$

2. Unjustified removals = 35% of total

$$Cs = \$1.65 \frac{C}{L}$$

3. Unjustified removals = 25% of total

$$Cs = \$1.15 \frac{C}{L}$$

9. Reorder Costs

At the organizational spares level, reorder takes place whenever the stock level is reduced to some specified level. Similarly, reorder may be made at depot level to replace lost or unrepairable units, although this would be on a much smaller scale. If it is assumed that spares held in stock could be reduced by the same percentage as the unjustified removals, then the reorder requirements will be reduced but the reorder frequency remains the same. For example, Figure 21 shows data that might represent typical stockkeeping. Here we have a situation in which initially 40 units/month are required for maintaining the fleet; the stock level is a maximum of 100 units; reorder takes place when the stock level is reduced to 60 units; and as a result of the order, 80 units are received 1 month later (this leaves a safety reserve of 20 units). The dashed lines show the situation resulting from the use of an FID when only 20 units/month are required for maintenance. The maximum stock level has now been reduced to 50 units, and reorder is initiated at a 30-unit level, allowing a minimum of 10 units before replenishment. As is apparent, the reorder frequency remains the same,

so no reorder processing life-cycle cost savings will result from using a fault-isolation device.

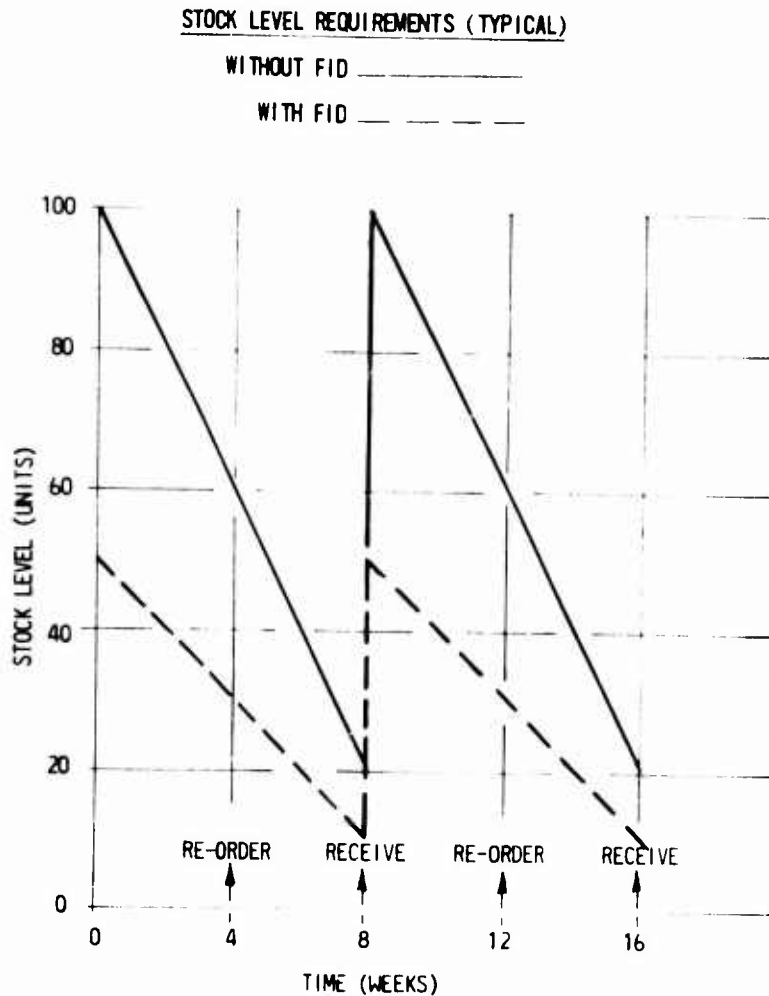


Figure 21. Stock Level Reorder Frequency.

10. Supply Administration

The overhead associated with supply administration should be amortized over the life cycle of the equipment. A fault-isolation device could have an indirect impact on these administrative costs, but attempting to speculate these impacts in terms of dollars would be beyond the scope of this program. As a result, it is assumed that these costs will remain unchanged.

11. Transportation, Handling and Storage

Whereas storage costs could not be considered a significant factor in the U.S. Army fuel control cost analysis, transportation and handling are recurring costs which are directly dependent on the maintenance history of the control. A direct reduction in fuel controls removed from aircraft installations will result in the same reduction in transportation and handling actions. For military transportation, the operating costs are not well defined (cannot be logically allocated to the fuel control unit alone), and the figures used in this study are based on the equivalent commercial transportation costs (average weight/mile rates). The definition of man-hours allocated to handling is also rather nebulous as to where time is booked to the maintenance action and where it becomes transportation handling. However, it is evident that any additional handling time that may occur is small when compared to the 3 hours for remove/replace at the field organizational level and 7 hours testing at the depot support level. This study has not included any cost for handling. Justification is in the likely magnitude of this figure (an order removed from the more significant manpower costs) if it had not already been included in other man-hour estimates. Transportation costs have been based on commercial rates, and a one-way packaging and shipping rate of \$0.23 per pound per trip has been estimated.

For the TA-2 fuel control with a weight of 30 pounds (includes power turbine governor and integrated pump), average package weight = 35 pounds.

$$\text{Cost per round trip} = 2 \times 35 \times \frac{23}{100} = \$16.00$$

$$\text{Mean time between removals} = 400 \text{ hours}$$

Therefore, in 1000 flight hours, transportation costs =

$$\frac{1000}{400} \times \$16.00 = \$40.00$$

For:

1. Unjustified removal = 50% of total

$$Cs = \$20.00$$

2. Unjustified removals = 35% of total

$$Cs = \$14.00$$

3. Unjustified removals = 25% of total

$$Cs = \$10.00$$

12. Salvage Credit

These are nonrecurring credits at the expiration of the program and are made up of all equipment, parts, facilities, etc., that can be reused or resold. All available evidence indicates that gas turbine fuel controls do not have any real salvage worth, and as a result, a fault-isolation device will not impact on this life-cycle cost aspect.

No allowance has been given to the phasing out period of the life cycle, where maintenance, particularly with respect to overhauls, can be reduced by reusing controls from scrapped aircraft.

13. Aircraft Operations

a. Aircraft Availability

The reduced maintenance time resulting from the use of a fault-isolation device should mean that aircraft availability is improved.

If this is utilized in terms of combat and training missions, then it could be postulated that the total fleet requirements could be reduced for the same mission schedule, and the life-cycle cost savings attributed to this could be used as a credit toward the FID. However, because of parallel maintenance policies and varying fleet requirements, it is virtually impossible to give real monetary significance to availability. Therefore, this study has not considered improved availability as a cost factor in computing the total potential cost savings associated with a fault-isolation device.

b. Aircraft Accidents and Aborted Missions

Aircraft accidents and aborted missions attributed to the fuel control unit may be reduced with an effective fault-isolation device. However, this is indirectly related to the objectives of the device, which are to detect the presence, or absence, of a fuel control fault at ground support level. This would not be true of a diagnostic device in which impending failures would be detected and appropriate action taken.

Fault-Isolation Techniques

The objective common to all of the fault-isolation techniques evaluated in this report is to establish a fuel control system fault-isolation device (FID) which will substantially reduce unjustified removals, and which is also compatible with the cost-effectiveness criteria established in the preceding section. Fault isolation is assumed to be required to identify faulty line replaceable assemblies (LRU's) rather than for isolating to failures of internal components such as gears, valves, bellows, flyweights, etc., which are replaced at the depot level. Also, the FID is assumed to be required only for internal failures which cause engine performance errors and not for visually discernible failures like fuel leaks.

The effectiveness of an FID is measured by its ability to correctly identify fuel controls with internal failures which degrade engine performance. One hundred percent effectiveness implies fault identification of the control for all such types of internal failures. It also implies that a correctly functioning control will never be identified as the failed component. To achieve this goal, the FID must respond to all possible failure modes that can affect performance, regardless of their probability of occurrence, and be free of failure modes of its own. This is not a practical goal, since any realistic mechanization of the fault-isolation functions is bound to be less than 100% reliable.

It is reasonable to expect that as the number of failure modes to which the FID is designed to be responsive increases, the more complex will be its mechanization requirements; therefore, its cost, size, and weight will increase and its reliability will decrease. A realistic effectiveness goal for the FID must be based upon the objective of cost effectiveness, defined at the beginning of this section, since an incorrect identification increases maintenance cost. However, 100% effective fault-isolation techniques are likely to require complex mechanization and can therefore be too expensive to be cost effective. On the other hand, fault-isolation concepts which are less than 100% effective, but do respond to a majority of the higher frequency failure modes in the control, might very well be acceptable on the basis of their cost effectiveness.

This section includes estimates of the cost and effectiveness for several technically feasible fault-isolation concepts to determine which is potentially the most cost effective approach. Since the type of control to which the FID is applied has a major impact on its feasibility and cost effectiveness, both current hydromechanical type and advanced electronic type fuel control FID applications are evaluated. The evaluation also includes FID concepts which provide ground test equipment (GTE) to be shared by a number of aircraft, as well as completely built-in test (BIT) FID techniques. The advantage of the former over the latter is that it enables the cost of the GTE to be shared by a number of fuel control units.

Trade-off Summary of FID Schemes

The various FID schemes described in detail in the following sections are summarized in Tables V and VI. Table V summarizes FID concepts applied to a typical current hydromechanical fuel control, while Table VI summarizes the same concepts applied to a future electronic-type control. Both tables include BIT and GTE fault-isolation schemes.

These tables facilitate a trade-off analysis by allowing quick comparisons of various FID schemes with respect to their weight, size, cost, advantages, and disadvantages. Since we are primarily interested in the impact of the FID on the control unit, the weight, size and cost are estimated in percentage of the control unit weight, size and cost. The hydromechanical and electronic type fuel controls, selected for FID applications, are approximately equal in functional complexity and cost (\$7,000). However, the electronic type control is half the size and weight of the 30-pound, 400-cubic-inch hydromechanical unit. Therefore, the impact of an FID scheme on control unit size and weight is significantly greater in an electronic type control than in a hydromechanical application.

For both types of controls, the redundant fuel control scheme provides close to 100% fault isolation and also improves aircraft mission reliability by enabling the pilot to substitute the standby control unit for a faulty on-line unit. However, this scheme more than doubles the weight, size and cost of the control system.

TABLE V. HYDROMECHANICAL FUEL CONTROL FAULT-ISOLATION SCHEMES TRADE-OFF STUDY SUMMARY							
Type	Description	Weight (% of Fuel Control)	Size (% of Fuel Control)	Cost (% of Fuel Control)	Basic Advantages	Basic Disadvantages	Remarks
1. Dual fuel control concept	Duplicate fuel control units with switchover facility for troubleshooting and backup	110	103	103	<ul style="list-style-type: none"> Approaches 100% effectiveness Improves aircraft mission reliability, availability, maintainability, and safety 	<ul style="list-style-type: none"> Cost prohibitive Duplicate systems increase vulnerability Problem of installation with present aircraft systems (size) 	High cost eliminates this as a candidate system
2. Model reference system	Electronic computer with independent sensors computes desired fuel flow and IGV position. These are compared to actual outputs sensed by metering valve and IGV position sensors.	25.7	29.0	52.2	<ul style="list-style-type: none"> 99 to 99.8% effective Flies on-line with aircraft Simple GO/NO-GO test 	<ul style="list-style-type: none"> Requires electro-mechanical sensors installed in hydro-mechanical control Requires costly high-performance computer Requires electrical power generation in hydromechanical control 	Not cost effective at present time
3. Threshold reference system	Special-purpose electronic logic unit compares threshold limits against metering valve and IGV positions for specific operating modes only.	18.0	19.0	18.7	<ul style="list-style-type: none"> Lower cost than 1&2 Flies on-line with aircraft Simple GO/NO-GO test 	<ul style="list-style-type: none"> Probably only 80-90% effective Increases probability of unjustified engine removal Requires electrical power & electro-mechanical sensors in hydromechanical control 	Not effective for present hydro/mech controls
4. Failure signature sensing	Hydrophonic, vibration, sonic, filter particle analysis and pressure sensing signals reflecting deterioration of internal fuel control parts	2.7	4.4	15.9	<ul style="list-style-type: none"> Potential of forecasting some imminent failures (wear) Compatible with engine health analysis techniques Could improve mission reliability 	<ul style="list-style-type: none"> Will probably detect only 10-20% of all failures Vibration/sonic analyzer expensive for fuel control alone Requires electro/mech sensors for hydro-mechanical control 	Majority of fuel control failures do not manifest characteristic signatures suitable for this type of analysis.
5. Fuel control self test	Open-loop check of fuel control at specific self-test calibration points. (Start, accel, decel, N_1 gov, N_2 gov)				<ul style="list-style-type: none"> Feasible on electronic type fuel controls only 	Not applicable for hydromechanical type fuel controls	Good potential for future electronic controls but not feasible for hydro/mech controls
6. Recorded fuel flow analysis	Plot of W_f vs. N_1 during engine start, accel and decel is compared to design curves for specified atmospheric conditions.	3.4	5.6	6.4	<ul style="list-style-type: none"> Would not require extensive fuel control modifications in present systems Flexible to changes in specifications Relatively low cost to incorporate 	<ul style="list-style-type: none"> Requires calibration curves and technical analyses Can not fault isolate during closed-loop governor performance Transient response of XY plotter may limit accuracy 	Required setup time and analysis detract from advantages. Effectiveness of approx. 85% does not meet required goals.
7. Ground integrated test equipment G.I.T.E.	Similar to Type 2 but used only as ground support equipment; that is, does not fly with aircraft	4.1	4.7	10.5	<ul style="list-style-type: none"> Size & weight not important Only 1 device per 5 aircraft required Can use ground electrical power 99 to 99.8% effective More comprehensive tests possible 	<ul style="list-style-type: none"> Not always available Requires built-in sensors on present fuel controls Requires longer set-up time For ground testing, the maximum allowable engine speed is limited to 70-85%. 	This would appear to be the only system that might be cost-effective with present-day fuel controls.

TABLE VI. ELECTRONIC TYPE FUEL CONTROL FAULT-ISOLATION SCHEMES TRADE-OFF STUDY SUMMARY							
Type	Description	Weight (% of Fuel Control)	Size (% of Fuel Control)	Cost (% of Fuel Control)	Basic Advantages	Basic Disadvantages	Remarks
1. Dual fuel control concept	Duplicate fuel control units with switchover facility for trouble- shooting and backup	120	106	103	<ul style="list-style-type: none"> Approaches 100% effective Improves aircraft mission reliability, availability, maintainability, and safety 	<ul style="list-style-type: none"> Cost prohibitive Duplicate systems increase vulnerability Problem of installation with present aircraft systems 	High cost eliminates this as a candidate system
2. Model reference system	a) Electronic computer with independent sensors and power supply computes desired fuel flow and IGV position. These are compared to actual output sensed by metering valve and IGV position sensors.	49.0	54.6	50.6	<ul style="list-style-type: none"> 99 to 99.8% effective Can be carried in cockpit Simple GO/NO-GO test 	<ul style="list-style-type: none"> Requires own power supply and electro-mechanical sensors Requires costly high-performance computer 	Not cost effective at present time
	b) Electronic computer, using control unit sensors and power supply, computes desired fuel flow and IGV position. These are compared to actual outputs sensed by control unit metering valve and IGV position sensors.	24.9	37.0	40.0	<ul style="list-style-type: none"> 95 to 99.4% effective depending upon control unit sensors and power supply reliability. Simple to interface with advanced electronic type fuel controls Can be carried in cockpit Lower in cost than option (a) Simple GO/NO-GO test 	<ul style="list-style-type: none"> Requires costly high-performance computer Less effective than option (a) 	Not cost effective at present time
3. Threshold reference system	Special-purpose electronic logic unit compares threshold limits against control unit metering valve and IGV position for specific operating modes only.	13.6	20.6	13.6	<ul style="list-style-type: none"> Lower cost than 1a2 Simple to interface to advanced electronic fuel control Can be carried in cockpit Simple GO/NO-GO test 	<ul style="list-style-type: none"> Probably only 80-90% effective Increases probability of unjustified engine removal 	Not cost effective at present time
4. Failure signature sensing	Hydrophonic, vibration and pressure sensing signals reflecting deterioration of internal fuel control parts	5.4	8.8	15.9	<ul style="list-style-type: none"> Potential of forecasting some imminent failures (wear) Compatible with engine health analysis techniques Could improve mission reliability 	<ul style="list-style-type: none"> Will probably detect only 10-30% of all failures Vibration/sonic analyzer expensive for fuel control alone 	Majority of fuel control failures do not manifest characteristic signatures suitable for this type of analysis
5. Fuel control self test	Open-loop check of electronic type fuel control computer at specific self-test calibration points. (Start, accel, decel, M_1 gov., M_2 gov.)	7.6	11.6	6.2	<ul style="list-style-type: none"> Does not require engine operation Simple GO/NO-GO test Cost effective on electronic fuel controls Built-in features (BIT) 	<ul style="list-style-type: none"> Probably only 90 to 95% effective Electronics is required to meet engine-mounted environment Requires ground power supply 	Good potential for future electronic controls
6. Recorded fuel flow analysis	Plot of M_2 vs. M_1 during engine start, accel to max and decel to idle is compared to design curves for specified atmospheric conditions.	4.3	7.0	4.5	<ul style="list-style-type: none"> Does not require fuel control modifications in present systems Flexible to changes in specifications Relatively low cost to incorporate 	<ul style="list-style-type: none"> Requires calibration curves and technical analyses Doubtful if maintenance personnel would use this system Transient response of TV plotter may not be sufficient 	Required setup time and analysis detract from advantages.
7. Ground integrated test equipment G.I.T.E.	Similar to Type 2 but used only as ground support equipment; that is, does not fly with aircraft.	8.2	9.4	10.2	<ul style="list-style-type: none"> Size & weight not important Only 1 device per 5 aircraft required Can use ground electrical power 99 to 99.8% effective More comprehensive tests possible 	<ul style="list-style-type: none"> Not always available Still requires sensors installed on present in-service engines Requires longer setup time Maintenance personnel may still change a control rather than test with this unit 	This would appear to be the only system that might be cost-effective with present-day fuel controls.

The model reference scheme is substantially lower in weight, size and cost than the redundant fuel control unit while still providing highly effective fault isolation. These economies are obtained by sacrificing fuel control redundancy, which is not a requirement for fault isolation. The model reference FID provides an electronic simulation of correct fuel control functioning which can be used to detect fuel control failure, but cannot functionally substitute for a failed control unit. Though much lower in cost than redundant fuel controls, the model reference FID costs far in excess of 10% of the control unit price limit for a cost-effective FID scheme. Its excessive cost is due primarily to its requirement for a high-performance electronic computer for simulating correct fuel control functioning.

The cost of the threshold logic computer is only one-third the cost of the high-performance model reference computer; however, it is unlikely that this threshold logic computer could be more than 90% fault-isolation effective. The threshold reference FID costs significantly more than the maximum allowable cost (10%), while its maximum potential effectiveness does not approach the minimum effectiveness (90%) required for a cost-effective FID. The threshold reference scheme is therefore not cost effective at the present time.

A further reduction in FID cost is possible in electronic type fuel control application by using self-test schemes for providing the fault-isolation function. This is feasible in electronic type controls which incorporate an electronic computer for generating control output signals from the measured input parameters. In the self-test scheme, the computer inputs are switched to calibrated reference settings and the computer outputs are compared to the expected output settings. Failure in the computer is indicated when any computer output exceeds its known output pressure drop (ΔP) across the main metering valve. The incorporation of a built-in self-test function in the electronic computer increases its cost slightly over 6% and produces only moderate increases in control unit weight and size. If optimally designed, a fuel control self-test FID should be able to provide up to 95% effective fault isolation.

The self-test scheme could, therefore, provide a cost-effective FID in future electronic type control applications. Its major disadvantage is that it is not technically feasible for hydromechanical control applications.

All of the FID schemes discussed above are provided as BIT equipment in the control unit. They require no ground test equipment and, except for the self-test scheme, require no ground power supply. They also provide a simple GO/NO-GO test for failure.

From the trade-off analysis, based upon the information given in Tables V and VI, we conclude that BIT fault-isolation schemes are unable to meet the established cost-effectiveness goals because they require a costly, high-performance, electronic computer to provide minimum fault isolation effectiveness. The only exception is the self-test scheme for electronic controls, which makes efficient use of the electronic computer and sensors already incorporated in an electronic type fuel control.

The remaining FID schemes in Tables V and VI require GTE and a power supply. Their primary advantage over the BIT schemes is that the high-performance electronic computer can be incorporated in the GTE, which can be shared by up to five aircraft. The cost of the electronics can therefore be shared by as many as seven fuel control units which would be required to support five aircraft. Electronic sensors and interfacing connectors must, of course, be provided for each control unit. This approach leads to a significant reduction in total FID cost per control unit while still providing highly effective fault isolation. The chief disadvantage, inherent in all GTE fault-isolation schemes, is that the maintenance personnel must obtain the ground test unit and connect it to the fuel control and the ground power supply before the fuel control can be tested. This setup time will be considerably longer than for a BIT system; and during busy intervals, a ground test unit might not be immediately available. This situation could induce maintenance personnel to revert to the present troubleshooting procedure of changing the fuel control units, thereby negating the purpose of the FID scheme.

Of the several GTE fault-isolation schemes evaluated, the recorded fuel flow concept is the least costly for both hydromechanical and electronic type fuel control applications. Although its cost falls well within the maximum allowable cost for FID applications, it suffers from the serious disadvantage of requiring complex calibration curves and technical analysis. It is doubtful if maintenance personnel could conveniently use this system. The ground integrated test equipment (GITE) scheme avoids this problem by applying the model reference concept, discussed above, to the GTE unit. Although its cost per control unit is slightly higher than the cost constraint, it requires minimal operating skills. For this reason, the GITE scheme is recommended for current hydromechanical fuel control fault isolation.

FID Descriptions

Preliminary details of the seven potential fault-isolation schemes discussed in the foregoing paragraphs are included in the following sections. Each includes a schematic block diagram of the functional requirements of the scheme with a brief description of the requirements necessary for incorporation into an aircraft maintenance structure. This is followed by a detailed evaluation of the selected GITE system including hardware and cost requirements.

1. Dual Control Concept

In this concept, fault isolation is obtained by providing redundant controls (Figure 22). Both controls are in operation; however, only one is controlling the engine fuel flow (W_F) and inlet guide vane (IGV). The other control, though physically disconnected from W_F and IGV, continues to receive the same input signals for computing W_F and IGV.

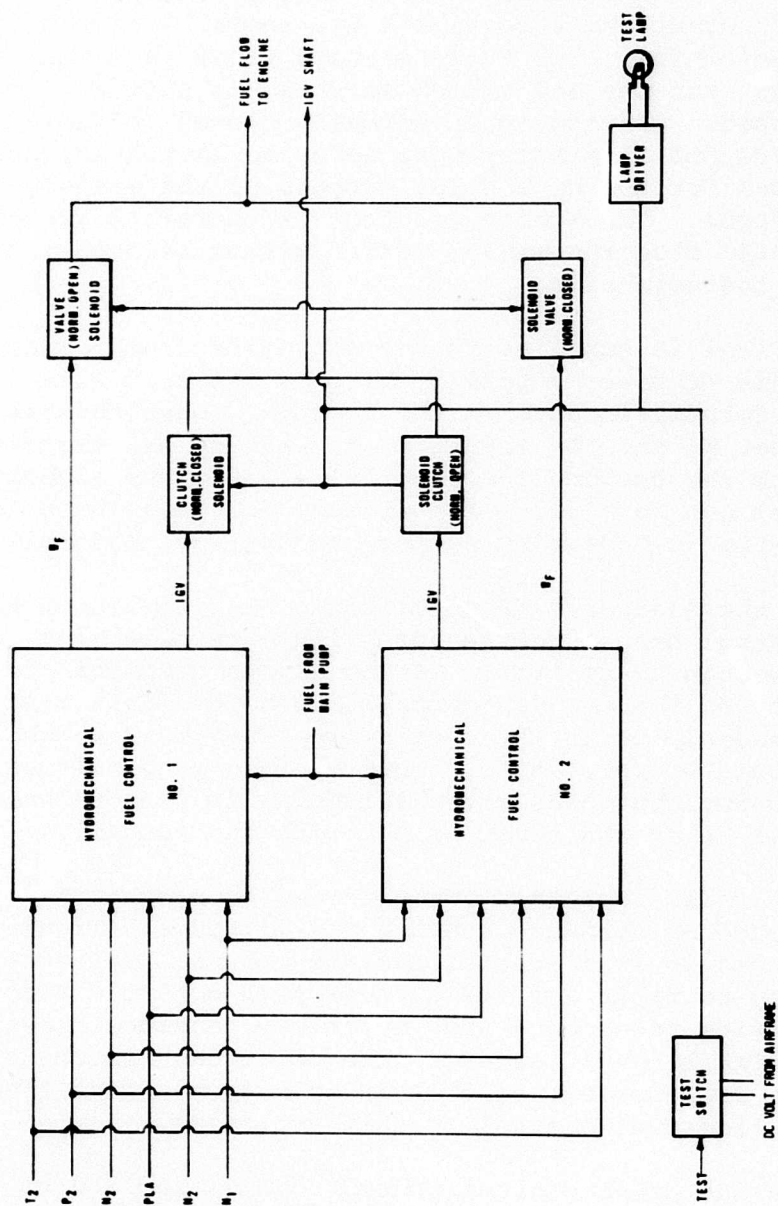


Figure 22. Dual Fuel Control FID.

Solenoid-operated fuel shutoff valves are provided in the W_F output line of each control to allow manual on/off switching of metered fuel flow to the engine. Similarly, solenoid-operated clutches enable manual connect/disconnect of the control IGV output shaft to engine IGV shaft. For the on-line control, the fuel solenoid valve is normally open, and the IGV clutch solenoid is normally closed. Conversely, a normally closed solenoid valve and a normally open solenoid clutch are provided for the W_F and IGV outputs of the standby control. The standby control is therefore disconnected from the engine until current is supplied to the solenoids.

Current is supplied to the solenoids from the airframe DC power supply by closing the test switch, preferably located in the cockpit. When this is done, W_F and IGV inputs to the engine are switched from the on-line fuel control (#1) to the standby fuel control (#2). A test lamp indicates when the engine is operating on the standby fuel control.

If the engine is malfunctioning, the on-line fuel control can be tested for failure by switching to the standby control. If the engine operates properly on the standby control, then the fault must obviously be in the on-line fuel control, which should be removed for repair. If engine malfunctioning continues after switching to standby control, then the fault is not with the control.

The fault-isolation function can be used both in ground maintenance testing and in actual flight; it requires no special test procedure. In addition to fault isolation, dual fuel controls also provide redundancy and, therefore, enhance mission reliability and safety. The pilot can switch to the standby fuel control if he suspects that the on-line fuel control is malfunctioning.

The dual fuel control concept can be applied to electronic type controls, as well as hydromechanical, and to present in-production controls, as

well as to future fuel controls if installation provisions are available. Its primary liabilities are that it more than doubles the cost and volume of the fuel control function, and is therefore the most costly of the several concepts which have been evaluated.

Estimated cost, size and weights for the dual hydro-mechanical and dual electronic FID are summarized below. Estimates are given in percentage of the fuel control unit cost, size and weight.

Dual Hydromechanical Fuel Control FID

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Hydromech. Fuel Control	100	100	100
Solenoid Clutches	1.4	1.5	5
Solenoid Valves	1.4	1.5	5
Indicator	0.2	Negli- <u>gible</u>	Negli- <u>gible</u>
Total	103.0	103.0	110

Effectiveness: Approaches 100%

Dual Electronic Type Fuel Control FID

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Electronic Type Fuel Control	100	100	100
Solenoid Clutches	1.4	3.0	10
Solenoid Valves	1.4	3.0	10
Indicator	0.3	Negli- <u>gible</u>	Negli- <u>gible</u>
Total	103.1	106.0	120

Effectiveness: Approaches 100%

2. Model Reference Fault Isolation

a. Hydromechanical Fuel Control

In the model reference concept, fault isolation depends upon the measurement of unacceptable fuel control performance. Control performance is measured by comparing control output signals, in this case W_F and IGV position, with corresponding signals computed by an electronic model of the correctly performing control. The model must be supplied with the same inputs as the fuel control. Therefore, in a hydromechanical application, all control inputs and outputs must be transduced into appropriate electrical input signals to the fault-isolation electronics. In addition, the FID electronics is provided with its own engine-driven alternator and regulated power supply, so that it can operate independently of air-frame power (see Figure 23).

From the control input signals, the fault-isolation electronics computes the desired fuel flow (W_F^*) and IGV position (IGV^*). Actual fuel flow W_F is computed in the fault-isolation electronics from fuel control metering valve position (X_m), measured by an LVDT position transducer, and the pressure drop across the main metering valve (ΔP) measured by a differential pressure sensor. The computed actual fuel flow (W_F) is then compared with the desired fuel flow (W_F^*). Any deviation of W_F from W_F^* generates an error signal, E_F , which is the measure of fuel flow control performance. Similarly, the deviation of measured IGV from IGV^* produces the error signal, E_V , which is the measure of IGV control performance.

Low-pass filtering is provided for both error signals before they are supplied to the thresholds fault-detection circuits. Low-pass filtering is required to suppress transient error signals due to unavoidable circuit noise and

Figure 23. Model Reference FID for Hydromechanical Control.

dynamic mismatch between the control and the reference model. The threshold detection circuits receive the filtered error signals and compare their amplitude with preset positive and negative threshold limits. If the signal amplitude remains within the preset limits, the control is assumed to be performing properly. On the other hand, if the signal amplitude exceeds either positive or negative thresholds, then performance is assumed to be degraded due to failure in the control and the failure lamp lights to indicate this condition to the operator.

A finite error signal is produced during normal operation by unavoidable static as well as dynamic mismatch between the model reference and actual control. The threshold levels must be set high enough so that the failure detection circuits will not be tripped during normal operation, thereby inadvertently indicating failure. However, if the threshold levels are set too high, the system will be insensitive to performance degradation produced by failures. These ambiguities must be avoided by designing the model reference to match normal control response as closely as possible. This insures that error signal excursion during normal operation will be small, so only actual control failures can produce error signals that are large enough to turn on the failure lamp.

Model reference fault isolation, like the dual controls concept, can be used in both ground maintenance testing and actual flight. It requires no special test procedure. Its ability to check control performance allows it to be used to detect incipient failures which first reveal themselves by producing small losses in performance which might otherwise go unnoticed. The model reference approach does not provide redundant fuel controls as does the dual control concept and can be used only as an FID.

Although significantly lower in cost and size than dual controls, it is still a fairly expensive approach to fault isolation, primarily because it requires a high-performance electronic computer to provide the model reference; and in the case of hydromechanical controls, electromechanical sensors are required for all control input/output signals.

b. Electronic Type Fuel Controls

Model reference fault isolation can be applied to electronic type controls in either of two ways as illustrated by Figures 24 and 25. The approach illustrated in Figure 24 provides the fault-isolation electronics with its own input sensors and power supply. Model reference computation in the FID is essentially the same as control signal computation in the actual control. Therefore, the FID provides the control with dual input sensors, a power supply, and an electronic computer. In the electronic application, the control is usually provided with output sensors for transducing MMV and IGV positions into electrical signals which can be used to compute W_F and IGV for comparison with W_F^* and IGV* in the FID. However, a differential pressure sensor is still required to transduce the metering valve pressure drop into an electrical signal.

Dual input sensors, a power supply, and an electronic computer enable the FID in this application to respond to any failure in the actual control which degrades its performance, including sensor and power supply failures. Output sensors need not be redundant because their failure will produce an error signal in the FID. The model reference FID functions the same way in electronic type controls as in the hydromechanical application, and provides the same advantages. Its requirement for redundant input sensors and an electronic computer produces a proportionally higher impact

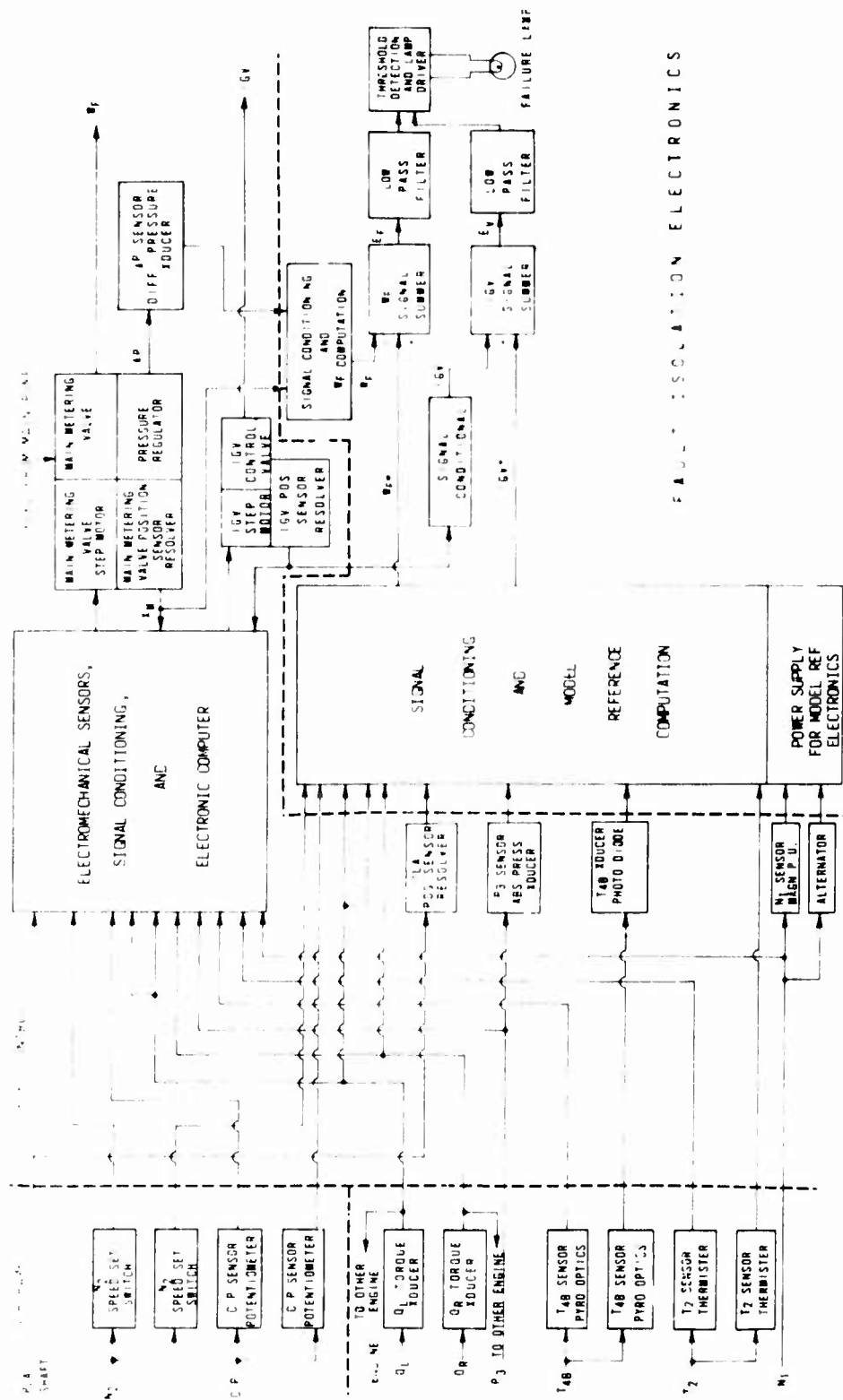


Figure 24. Model Reference FID for Electronic Type Control.

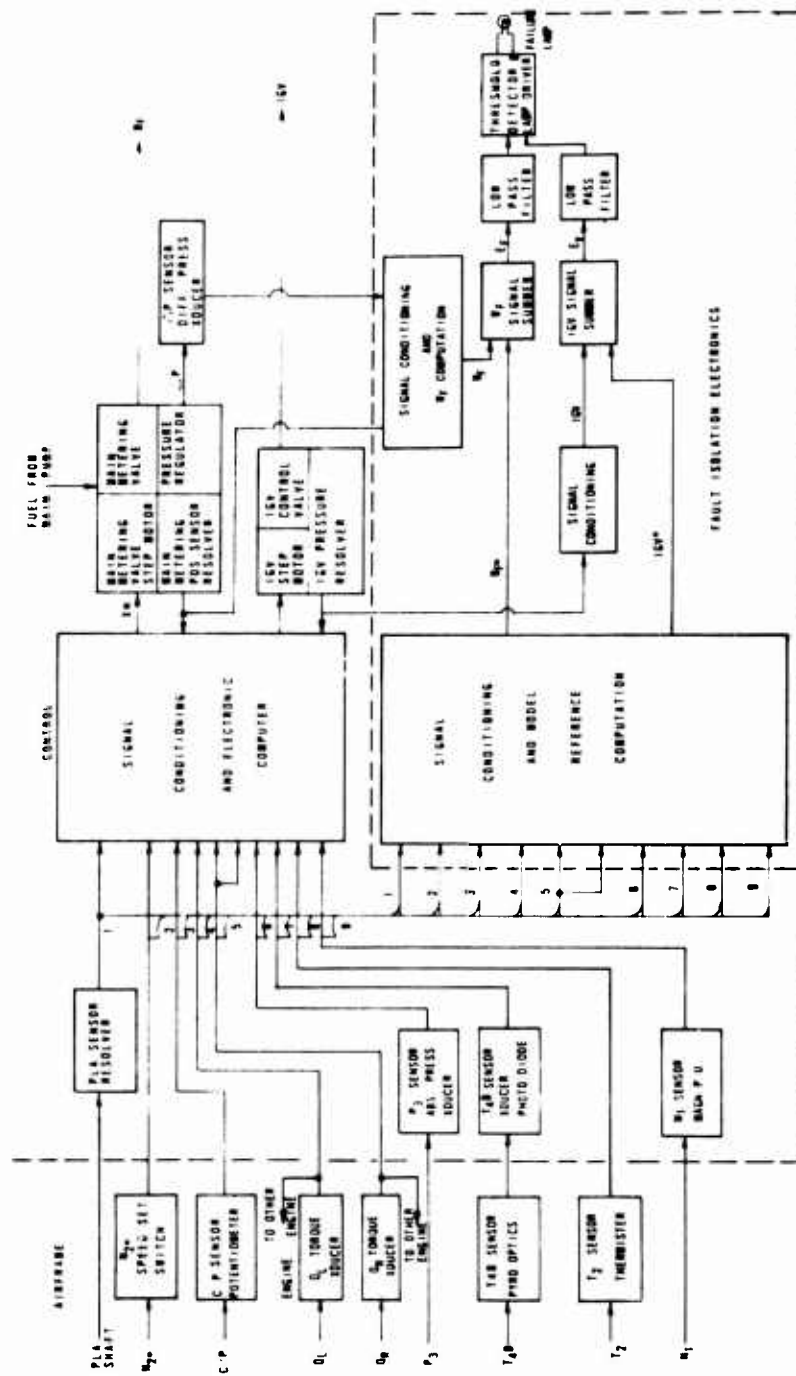


Figure 25. Model Reference FID for Electronic Computer and Fluid Controller.

on control cost, weight, and size. The added weight and volume are the same as in the hydromechanical application; however, electronic type controls are lighter and smaller.

The concept, presented in Figure 25, produces a significant cost reduction from the fully redundant system of Figure 24 by using the electrical power and sensors from the engine control for model reference computation. Therefore, only the electronic computer need be duplicated in the control. The model reference FID in this application would be designed to be responsible to input sensor or power supply faults by using a computing technique in the FID that is different from the computation methods used in the control.

Hydromechanical Fuel Control Model
Reference FID

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Electronics	38.6	17.2	11.7
Sensors	12.4	6.4	5.6
Alternator	1.0	5.4	8.4
Indicator	0.2	Negli- <u>gible</u>	Negli- <u>gible</u>
Total	52.2	29.0	25.7

Effectiveness: 99 - 99.8%

Electronic Type Fuel Control Model Reference FID
(Redundant Sensor and Power Supply)

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Electronics	38.6	34.4	23.3
Sensors	10.8	9.4	9.0
Alternator	1.0	10.8	16.7
Indicator	0.2	Negligible	Negligible
	_____	_____	_____
Total	50.6	54.6	49.0

Effectiveness: 99 to 99.8%

Electronic Fuel Control Model Reference FID
(Utilizes Sensor and Power Supply From the Fuel Control)

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Electronics	38.6	34.4	23.3
Sensors	1.2	2.6	1.6
Indicator	0.2	Negligible	Negligible
	_____	_____	_____
Total	40.0	37.0	24.9

Effectiveness: 95 - 99.4%

3. Threshold Reference FID

a. Hydromechanical Fuel Control

The Threshold Reference Fault Isolation Device (TRFID), Figure 26, for a hydromechanical control is designed to respond to critical gross performance degradation modes in the fuel control rather than to a change in measured performance. The TRFID indicates failure only

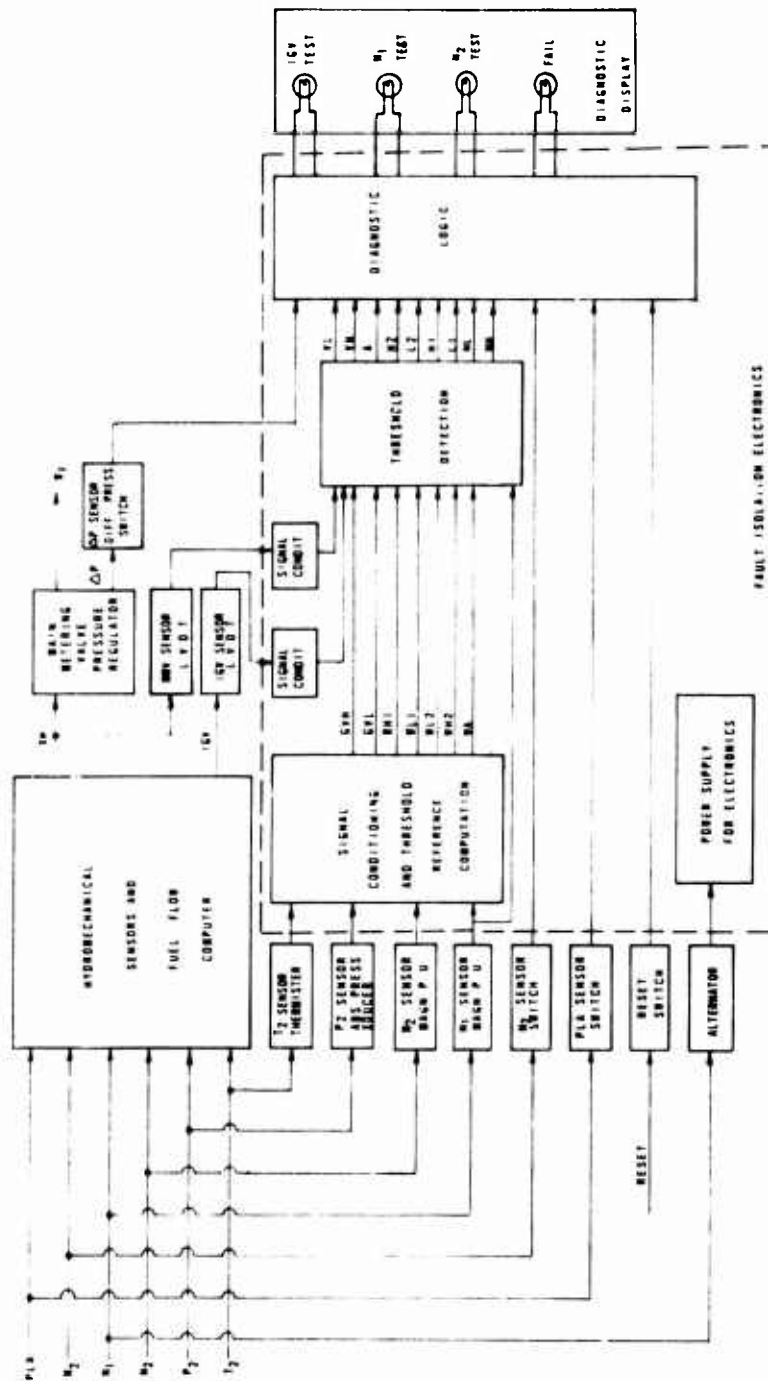


Figure 26. Threshold Reference FID for Hydromechanical Control.

when measured fuel flow exceeds preset limits during start, deceleration, N_1 idling, and N_2 governing operation. It is not responsive to performance degradations that occur in other than the selected operating modes.

Referring to the system block diagram shown in Figure 26 and the fuel schedules shown in Figure 27, the TRFID operates as follows:

Main metering valve position (X_m) (which is proportional to fuel flow W_F), metering valve pressure drop (ΔP), gas generator speed (N_1), power turbine speed (N_2), compressor inlet pressure (P_2), and compressor inlet temperature (T_2) are sensed by the appropriate transducers and supplied as electrical input signals to the TRFID electronic package. N_1 and N_2 are used to compute the upper and lower limits on W_F for normal operation during start to engine idling and during N_2 governing. These limits are generated as segmented straight-line functions of N_1 and N_2 (see Figure 27). P_2 and T_2 are used as bias signals to compensate these limits for altitude and temperature changes. $WH1$ and $WL1$ provide the upper and lower bounds on W_F for normal starts and decelerations, while $WH2$ and $WL2$ similarly set the upper and lower bounds on W_F for normal operation during N_2 governing. WA , together with $WH1$, defines the operating region in which the power turbine governor normally controls the engine. Similarly, upper GVH and lower GVL bounds are computed for IGV position schedule.

The computed W_F and IGV limits, together with the measured W_F and IGV, are supplied to threshold detectors. Here, measured W_F and IGV are compared with the boundary signals. If measured W_F or IGV is lower or higher than the boundary signal, a corresponding threshold logic signal will be switched to zero or one, respectively. A threshold logic signal is provided for each upper and lower bound on W_F

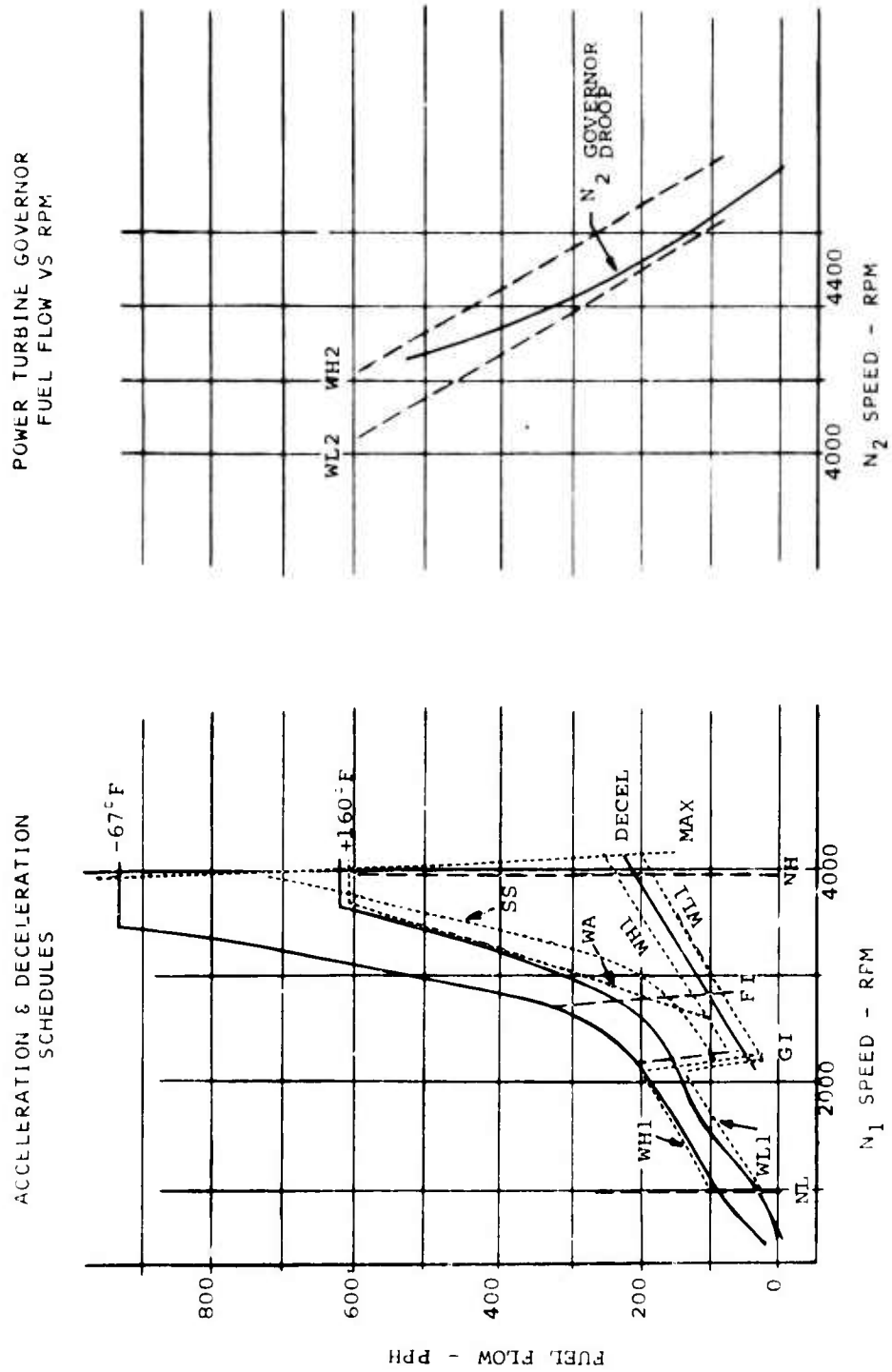


Figure 27. Threshold Reference Fuel Schedules.

and IGV, and also for the upper and lower bounds (NH and NL) of the N_1 speed range in which the TRFID is operational.

The threshold logic signals, VL through NH, together with the N_1^* speed select, N_2^* speed select, ΔP , and reset switching signals are supplied as inputs to the TRFID logic. The output of the TRFID logic is several lamps; i.e., IGV test, N_1 test, N_2 test and failure. In addition, a flag is provided with each lamp.

When the operator sets N_1^* and N_2^* for engine idling and the engine is above maximum cranking speed (NL), the TRFID will check out the acceleration/deceleration and N_1 droop schedule. This operation is indicated to the operator by the lit N_1 test lamp. If W_F exceeds the upper WH1 or lower WL1 bounds, the TRFID logic will switch the failure lamp on, and both failure and N_1 test will be flagged until the reset button is pressed.

If W_F remains within its normal operating bounds throughout the N_1 test period, the operator may proceed with the N_2 governing and IGV test by setting N_1^* and N_2^* to the power position (P). When the engine is operating in the range where W_F is less than W_A , but higher than WH1, and N_1 is less than 100% speed (NH), then the TRFID logic switches the N_2 test lamp ON, indicating that the N_2 governor droop and IGV schedule are being checked out. Again, if W_F should exceed its normal upper and lower bounds (WH2 and WL2) during this operation, the TRFID logic switches on the failure lamp and both failure and N_2 test will be flagged until the reset button is pressed. Similarly, if IGV should exceed its normal bounds (GVH or GVL), the IGV lamp as well as the failure lamp switches ON. Failure of ΔP signal during either test will also cause the failure lamp to switch ON.

In concluding, it should be pointed out that the TRFID will perform only from engine idling up to approximately 20% power or when N_1 is between top cranking speed and 80%. It would be advisable to press the reset button before each test to ensure that the TRFID logic is not locked into a failure condition due to a previous operation or a power transient. The TRFID is provided with its own engine-driven alternator and regulated power supply. It can therefore operate independently of airframe or GSE power.

In the hydromechanical control, the TRFID must be provided with the same input and output sensors as in the model reference concept, but it requires far simpler fault-isolation electronics. The TRFID technique obtains circuit simplicity and thereby lower cost by sacrificing the broad performance and operating range possible with the model reference technique.

The TRFID performance level depends upon the extent to which actual failure in the fuel control produces the critical performance degradation modes to which the TRFID is sensitive. In considering the overall system performance, it seems that a majority of component failures will produce either excessively high or excessively low fuel flow during acceleration, deceleration, or droop governing in the pre-mission engine idling (I) or 80% speed (P) modes.

Hydromechanical Fuel Control With
Threshold Reference FID

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Electronics	12.2	9.0	6.0
Sensors	5.1	4.6	3.6
Alternator	1.0	5.4	8.4
Indicator	0.2	Negli- gible	Negli- gible
Total	18.5	19.0	18.0

Effectiveness: 80 - 90%

b. Electronic Type Fuel Controls

The TRFID concept can be applied to electronic type controls as illustrated by Figure 28. Since the primary objective of the threshold reference approach is to reduce cost, the TRFID, in this application, uses the fuel control power supply and sensor signals. The only additional sensor required by the TRFID is a differential pressure transducer for sensing ΔP across the main metering valve. Otherwise, TRFID function and signal processing in electronic type controls is similar to that in hydromechanical applications.

The TRFID will be sensitive to failures occurring in the control computer and fluid controller which produce the critical performance degradations to which the TRFID is sensitive. For effective fault isolation with this TRFID concept, it is necessary that most of the high-probability failures that occur in electronic type controls fall into this category.

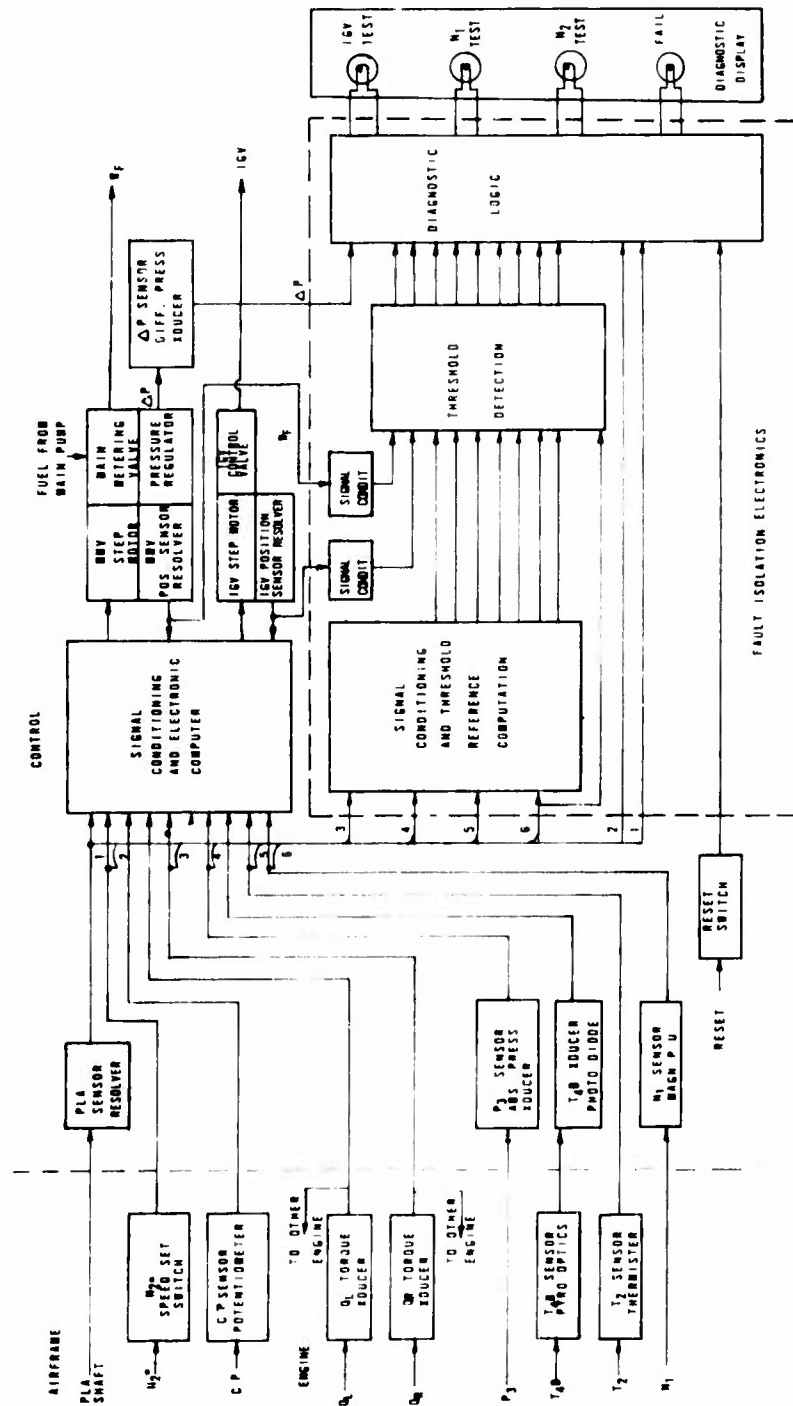


Figure 28. Threshold Reference FID for Electronic Type Control.

Electronic Type Fuel Control With
Threshold Reference FID

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Electronics	12.2	18.0	12.0
Sensor	1.2	2.6	1.6
Indicator	0.2	Negli- gible	Negli- gible
Total	13.6	20.6	13.6

Effectiveness: 80 - 90%

4. Failure Signature Sensing

a. Vibration

Diagnostics by means of vibration spectrum analysis has been applied successfully to gas turbine engines. This has correctly indicated incipient wear and deterioration in rotating parts such as main engine bearings, fans, turbines and compressor blades and stators, and accessory gearboxes and drives. It follows that such techniques could be applied to the rotating parts of the fuel control unit with perhaps equal success in correctly diagnosing wear and deterioration. Fuel control parts which may fall into this classification would be:

Gas generator speed drive coupling

Power turbine speed drive coupling

Fuel pump primary gear assembly

Fuel pump secondary gear assembly
(if applicable)

All rotating servo valve assemblies

Governor flyweights (gas generator and power turbine)

All speed drive bearings

Figure 29 is a block diagram of the type of hardware configuration required for this type of analysis. The complexity of the system required is apparent, and estimates based on presently available commercial equipment indicate that it would be far too costly for this application alone. For systems which already include vibration analysis for indicating engine deterioration, including the fuel control and pump in the analysis would probably be cost effective. However, confirmation that the relevant vibration signals lend themselves to such an analysis would be necessary before a final decision could be made. This would require correlating experimental vibration data taken from faulty fuel controls with that taken from healthy ones.

b. Sonic Analysis

Sonic analysis is very similar to vibration analysis and in general covers the same range of fault diagnosis. In some cases, a signal is better received in audio rather than vibratory form, but generally vibration has shown more potential for engine health analysis. The cost of a sonic analyzer can be expected to be of the same order as a vibration analyzer, and therefore the possibility of using both systems for optimum performance can be disregarded completely. For these reasons sonic analysis of fuel controls has not been considered further.

c. Fluid Pressures

By monitoring the following fuel pressures, indications of fuel control deterioration in

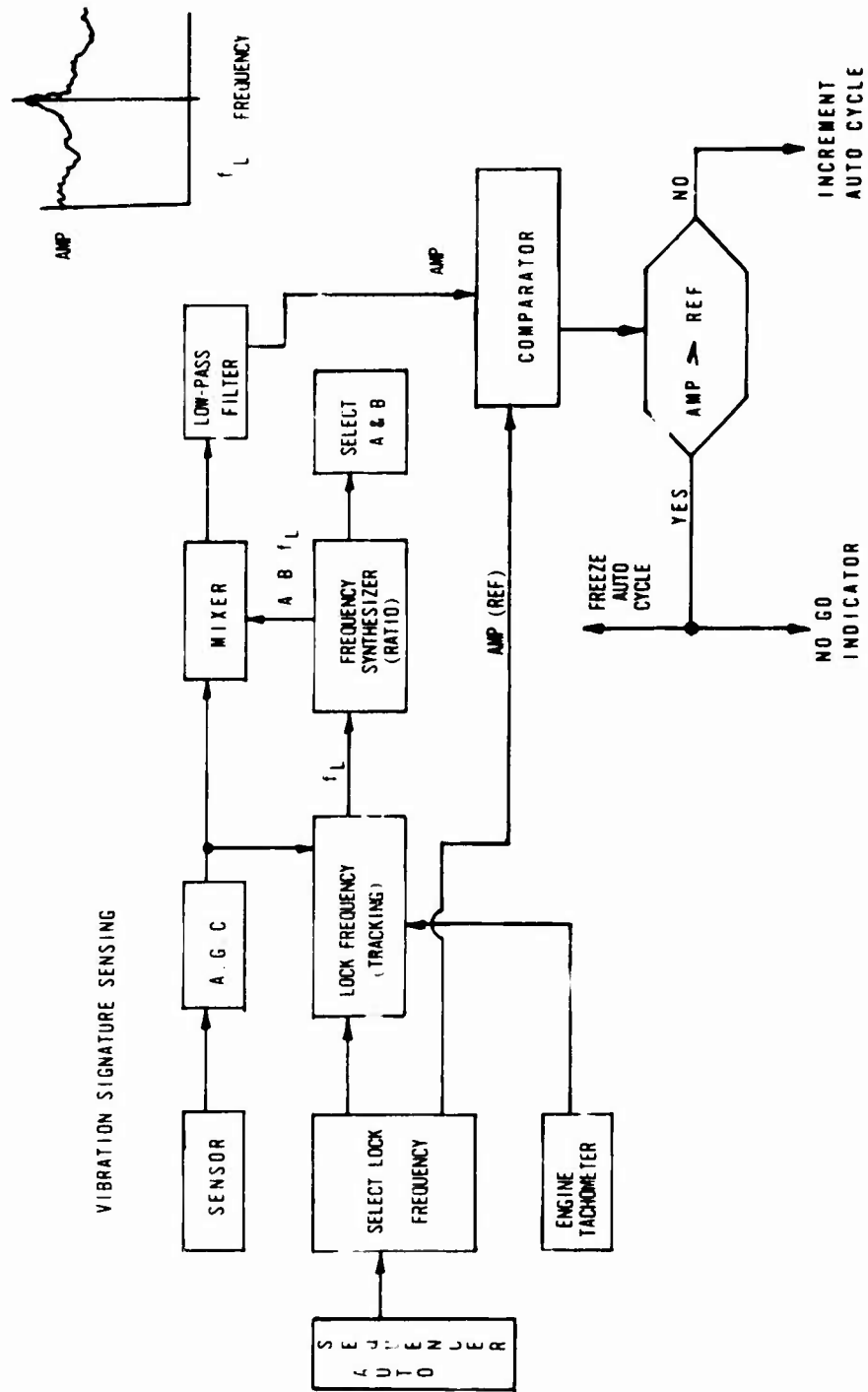


Figure 29. Vibration Analysis Block Diagram.

the pumping and regulating sections may be evident:

Pressure drop across pump inlet filter

Pressure drop across metering valve

Pressure drop across servo flow filter

Servo flow fluid pressure

Pump inlet pressure

Pump exit pressure

d. Fluid Temperatures

Efficiency losses through deterioration of rotating parts invariably result in increased temperatures. However, this parameter would apparently offer no more information than could be obtained by a vibration analysis. In addition, separation of temperature rises resulting from deteriorating parts from those caused by the many other variables which may influence the fluid and metal temperatures would be involved, calling for complex and expensive hardware. Complexity and limited diagnostic information preclude this from further consideration.

e. Filter Particle Analysis

By filtering the fuel control output flow and periodically analyzing the particle count, an indication of excessive fuel control or pump wear may be evident. Ruptured or worn seals resulting in excessive filtered particles of the seal material could indicate imminent internal or external leaks. Metal particles may indicate wear in pump gears, drive splines, servo valves, flyweights, bearings or cams and followers. Particle sizes greater than 50 microns could be removed at the pump inlet by

a suitably sized filter, while a coarse filter in the metered fuel outlet line could collect particle sizes greater than 100 microns. Automatic monitoring of particle count, although possible, would be far too costly for this application. It would therefore be necessary, as part of a scheduled maintenance routine, to send the hermetically sealed filter to a laboratory for microscopic analysis.

Although this system shows promise for fuel control condition analysis, it would obviously not lend itself to rapid fault isolation and diagnosis. Also, a large percentage of the random fuel control faults that occur would not be detected by this system.

Conclusion

It is apparent, when looking for characteristic failure signatures in fuel controls, that only a small percentage of all failures show these types of impending telltale signs.

The majority of failures occur in the fuel control computing sections, and in these cases manifestation is in performance only. A typical example, taken from actual operational data, is a material chemical reaction which caused a slow growth in a compressor inlet temperature bellows. Eventually this caused the engine performance to noticeably deteriorate. There appears little possibility of detecting this type of deterioration by any signature other than fuel control performance measurement. For fault-isolation effectiveness, it is imperative that a majority of potential failures be recognized. Therefore, it is necessary for absolute performance measurements to be used to achieve this objective, and no advantage will be gained by also using failure signature sensing in the isolated cases where it is applicable.

Hydromechanical Fuel Control With Failure
Signature Sensing FID

Fuel Control Unit Installation (Sensors)

<u>Type</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Vibration	3.6	Negli- gible	Negli- gible
Servo Pressure	1.7	1.3	0.8
Regulated Pressure	1.2	1.3	0.8
Filter Pressure	1.2	1.3	0.8
Connector	<u>0.1</u>	<u>0.5</u>	<u>0.3</u>
Total for Fuel Control Installation	7.8	4.4	2.7

Ground Test Unit (Electronics)

<u>Type</u>	<u>Cost</u>
Vibration	50
Servo Pressure	3
Regulated Pressure	3
Filter Pressure	<u>1</u>
Total for Ground Test Unit Electronics	57

Ground test unit can serve 5 aircraft or
7 control units, including 2 spares.
Therefore:

$$\text{Electronics cost per control unit} = \frac{57}{8} = 8.1$$

$$\text{Total cost per control unit} = 7.8 + 8.1 = 15.9$$

Effectiveness: 10 - 20%

Electronic Type Fuel Control With Failure
Signature Sensing FID

Fuel Control Unit Installation (Sensors)

<u>Type</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Vibration	3.6	Negli- gible	Negli- gible
Servo Pressure	1.7	2.6	1.6
Regulated Pressure	1.2	2.6	1.6
Filter Pressure	1.2	2.6	1.6
Connector	<u>0.1</u>	<u>1.0</u>	<u>0.6</u>
Total for Control Unit Installation	7.8	8.8	5.4

Ground Test Unit (Electronics)

<u>Type</u>	<u>Cost</u>
Vibration	50
Servo Pressure	3
Regulated Pressure	3
Filter Pressure	<u>1</u>
Total for Ground Test Unit Electronics	57

Ground test unit can serve 5 aircraft or
7 control units including 2 spares.

Therefore:

$$\text{Electronics cost per control unit} = \frac{57}{7} = 8.1$$

$$\text{Total cost per control unit} = 7.8 + 8.1 = 15.9$$

Effectiveness: 10 - 20%

5. Fuel Control Self Test

Built-in self test is not viable for hydromechanical and pneumatic fuel controls. An accurate mechanical drive source would be required to develop the necessary fluid and/or air pressures for computer operation, and this would require some type of clutch assembly in the accessory gearbox to allow the selection of an alternate ground support power drive. This also means dependence on ground support equipment, which immediately detracts from any advantage the system may have over full ground support test equipment.

For electronic type fuel controls which will probably be introduced by the late seventies, built-in self test appears to offer a definite advantage. Figure 30 is a block diagram of a typical electronic fuel control system with built-in self test as shown. All functional elements of the electronic control are checked for correct operation by attempting to drive the metering valve to a desired set position and comparing this to the actual position indicated by the feedback metering valve position transducer. The advantage of this system is the relative ease and low cost of incorporation. Also, the engine is not required to be running, thereby avoiding any likelihood of overstressing the engine while troubleshooting the fuel control. That is, a fault in the fuel control which may have caused excessive internal engine temperatures can be detected without the risk of further overtemperaturing the engine.

In conjunction with the self-test facility for the computing section of the fuel control, the system will also include a fluid controller fault isolation scheme. This relies on measuring the pressure drop across the metering valve and comparing it to the desired regulated pressure drop. Deviations outside allowable tolerances will cause the system to activate a NO-GO flag. This portion of fault isolation requires the engine to be running.

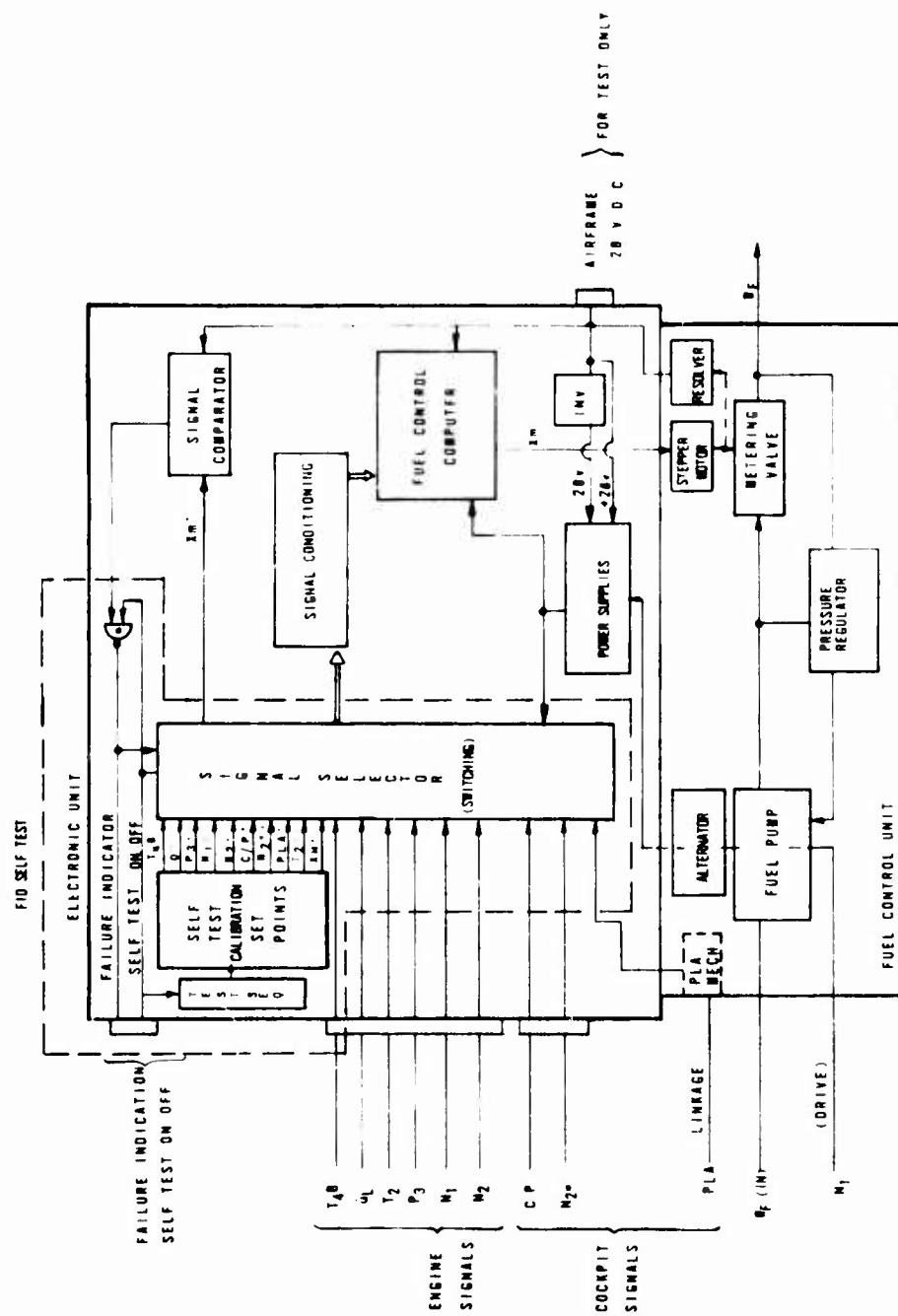


Figure 30. Built-in Self-Test FID for Electronic Type Control.

As a combination, this system should offer a high confidence level not only in fault-isolation effectiveness but also in the operability of the control by using the self test as a preflight verification check-out.

Electronic Type Fuel Control With Self-Test FID

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Electronics	5.0	9.0	6.0
Sensor	<u>1.2</u>	<u>2.6</u>	<u>1.6</u>
Total	6.2	11.6	7.6

Effectiveness: 90 - 95%

6. Recorded Fuel Flow Analysis

Figure 31 indicates a system in which the fuel control has been instrumented for fuel flow rate and gas generator rotor speed. The outputs are in the form of DC voltages which are used as the Y and X inputs to a plotter. During ground fault isolation, the maintenance technician connects the plotter to the fuel control unit and plots fuel flow versus speed for a specific engine start, accel, decel procedure. He then selects the appropriate template performance trace for the specific atmospheric temperature and pressure, and checks the recorded trace against the specified limits. The advantage of this system is its simple mechanization, low cost (see Tables V and VI), and the minor modifications that would be required of present-day operational controls. The main disadvantages are in the setup time and analysis required, and also in the limitations of the check-out. Start, acceleration and deceleration fuel flows can be checked with a high degree of confidence, but there may still be a degree of ambiguity in closed-loop governor performance when instability exists. The number of templates required would depend on the accuracy of the check-out. Typically, 40 templates

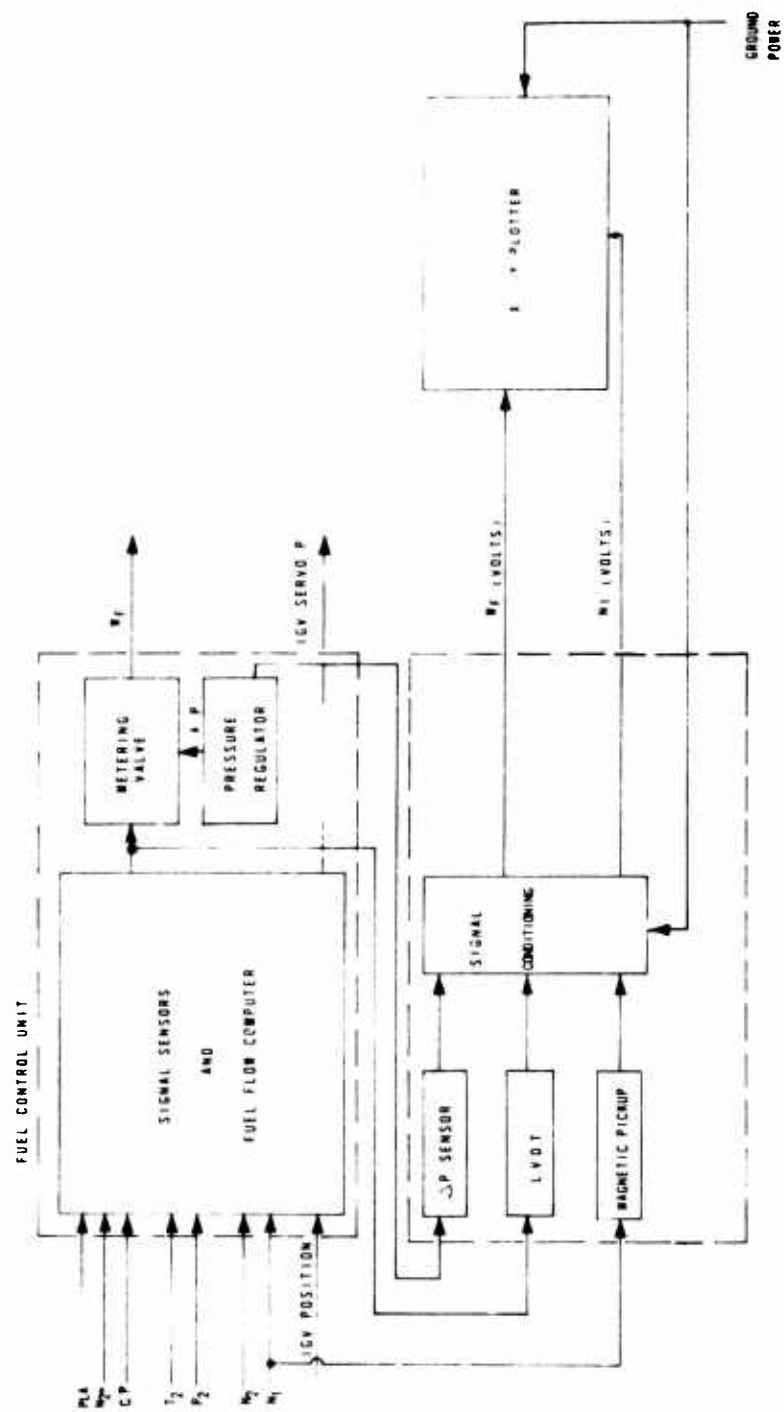


Figure 31. FID by Recorded Performance Analysis.

would give a resolution of 20°F in temperature and 0.5 psi in atmospheric pressure. This could be reduced considerably once the ground operating base was established. That is, for a base at a given elevation, variations in atmospheric temperature and pressure will be considerably less than the ceilings specified for worldwide use.

Electronic Type Fuel Control With Recorded Fuel Flow FID

Fuel Control Unit Installation

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Electronics	2.2	3.4	2.1
Sensors	1.2	2.6	1.6
Connector	<u>0.1</u>	<u>1.0</u>	<u>0.6</u>
Total for Control Unit Installation	3.5	7.0	4.3

Ground Test Unit (XY Recorder)

Ground Test Unit cost = 7.0

Ground test unit can serve 5 aircraft or 7 fuel control units including spares.

Therefore:

$$\text{Cost per control unit} = \frac{7.0}{7.0} = 1.0$$

$$\text{Total cost per control unit} = 3.5 + 1.0 = 4.5$$

Effectiveness: 80 - 85.0%

Hydromechanical Fuel Control With Recorded
Fuel Flow FID

Fuel Control Unit Installation

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Electronics	3.2	2.5	1.5
Sensors	2.1	2.6	1.6
Connector	<u>0.1</u>	<u>0.5</u>	<u>0.3</u>
Total for Fuel Control Installation	5.4	5.6	3.4

Ground Test Unit (XY Recorder)

Cost per test unit = 7.0

Ground test unit can serve 5 aircraft or
7 fuel control units including spares.
Therefore:

$$\text{Cost per control unit} = \frac{7.0}{7.0} = 1.0$$

$$\begin{aligned}\text{Total cost per control unit} &= 5.4 + 1.0 \\ &= 6.4\end{aligned}$$

Effectiveness: 80 - 85.0%

7. Ground Integrated Test Equipment (GITE)

Figures 32 and 33 indicate fault isolation using comprehensive ground equipment for a hydromechanical and an electronic fuel control respectively. Each fuel control unit is instrumented for all signals necessary for complete performance diagnosis.

Typically, a hydromechanical fuel control would require magnetic speed pickups located at the pump and the power turbine governor drive splines respectively, a linear variable differential transformer (LVDT) for measuring the metering valve

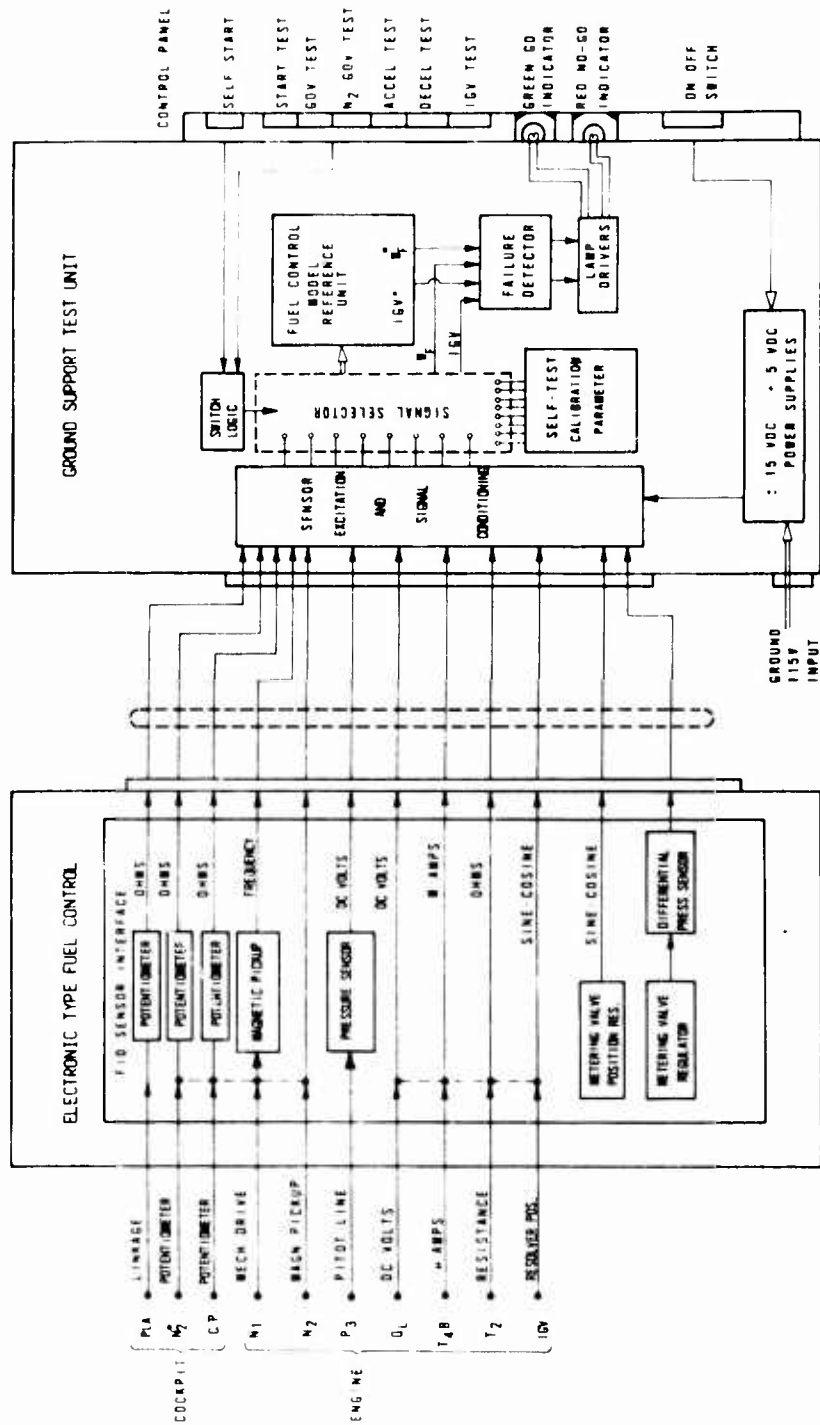


Figure 33. Ground Integrated Test FID for Electronic Type Control.

displacement, rotary variable differential transformer for PLA, N_2^* and IGV positions, and pressure sensors for measuring metering valve differential pressure and compressor inlet/outlet pressure. An electrical connector at the fuel control housing is used to interface the sensors to the ground test equipment.

The ground test unit contains the power supplies, signal processing circuits, fuel control model reference comparator, and failure detection circuit plus a control panel with the necessary functional test switches. To functionally verify the operation of the test equipment, a self-test feature has been included as part of the ground test unit. By selecting self test at the control panel, the operator can verify the operation of each fuel control check mode. Any failure, either in self test or during actual fuel control operational checks, will be indicated by a NO-GO lamp at the control panel. Assuming the availability of the test unit at the aircraft, the fuel control checkout time is estimated at a maximum of 25 minutes. This allows for removal of the engine cowling, connecting the unit to the fuel control, a self-test verification check, and the functional test in which the engine is started, accelerated to 80% speed, and decelerated to flight idle. Faults which prevent the engine from starting would be detected as an incorrect start fuel flow while the engine was being turned over by the starting mechanism, and would be indicated at the control panel of the test unit.

The GITE concept provides highly effective fault isolation by using the model reference technique for testing control unit performance. It avoids the high cost of the model reference concept by providing electronic computation in the GITE unit, the cost of which is shared by several fuel control units.

Hydromechanical Fuel Control With Ground
Integrated Test Equipment FID

Fuel Control Unit Installation
(Engine Sensors)

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Sensors	5.7	4.2	3.8
Connector	<u>0.1</u>	<u>0.5</u>	<u>0.3</u>
Total for Control Unit Installation	5.8	4.7	4.1

Ground Test Unit
(Electronics + Atmos. Sensors)

<u>Component</u>	<u>Cost</u>
Electronics	31
Sensors	<u>2</u>
Total for ground test unit	33

Ground test unit can serve 5 aircraft or
7 control units including spares.

Therefore:

Ground test unit cost per control unit
 $= \frac{33}{7} = 4.7$

Total cost per control unit = 4.7 + 5.8
= 10.5

Effectiveness: 99 - 99.8%

Electronic Type Fuel Control With Ground
Integrated Test Equipment FID

Fuel Control Unit Installation
(Engine Sensors)

<u>Component</u>	<u>Cost</u>	<u>Size</u>	<u>Weight</u>
Sensors	5.7	8.4	7.6
Connector	<u>0.1</u>	<u>1.0</u>	<u>0.6</u>
Total for Control Unit Installation	5.8	9.4	8.2

Ground Test Unit
(Electronics)

Cost per test unit = 31

Ground test unit can serve 5 aircraft or
7 control units including spares.
Therefore:

Ground test unit cost per control unit
 $= \frac{31}{7} = 4.4$

Total cost per control unit = 4.4 + 5.8
= 10.2

Effectiveness: 99 - 99.8%

Ground Integrated Test Equipment (GITE)

In the preceding section, a preliminary evaluation of a number of FID concepts established that the GITE scheme is the only cost-effective concept applicable to present hydromechanical fuel controls. This section provides a more detailed evaluation of the GITE system for the purpose of providing better estimates of its cost, size and weight impact upon the fuel control unit, and to establish its operational requirements in the maintenance procedure. The evaluation is based upon a preliminary design of the GITE described below.

Figure 32 provided a system block diagram of the GITE depicting its major components, their location, and their interrelationships. The basic philosophy of the GITE concept is manifest in this figure. All the transducers required for sensing fuel control inputs and outputs are located in the fuel control unit except for the P_1 and T_1 transducers. These two sensors are located in the Ground Support Test Unit (GSTU) since their purpose is to provide atmospheric condition inputs to the fuel control model reference unit and since testing is always performed on the ground. The output of these sensors should be the same in magnitude as the P_2 and T_2 inputs to the fuel control. The control unit is also provided with a single electrical connector and shielded cable through which all of the transducers are connected to the electronics located in the GSTU.

The GSTU includes all of the electronics required for fault isolation, signal processing, electrical power supplies, test controls, and fault indicators as well as the P_1 and T_1 atmospheric sensors. The GSTU can be shared by as many as five aircraft. Because all of the complex electronics required for effective fault isolation are located in this package, its cost can be shared by as many as seven fuel control units, thereby substantially reducing the unit cost.

Sensors

Nine sensors in all are required to provide the GITE inputs. Seven of these must be built into the fuel control unit, while two for measuring atmospheric pressure and temperature are installed in the GSTU. The selected sensors are listed in Table VII, which also gives their

TABLE VII. SENSOR REQUIREMENTS FOR FAULT ISOLATION OF HYDROMECHANICAL FUEL CONTROL

A. SENSORS BUILT INTO FUEL CONTROL										
Designation	Description	Measurement Range	Sensor Type	Sensor Range	Estimated Overall Accuracy	Volume (in.)	Weight (oz)	Input Power Requirements	Output Signal	Estimated Cost (> 100 Units)
1	HP Pressure Across Metering Valve	15-22 PSI	Bonded Strain Gauge Differential Pressure	0-25 psi	± 4.0% F.S.	2.5	2.0	10 VDC	30 M.V. Minimum	\$95
2	Metering Valve Position (X _M)	0-0.25 in.	Linear Variable Differential Transformer	0-0.3 in.	± 2.0% F.S.	2.0	1.2	6.3 V RMS 1-20 KHz (Not Critical)	Typically 1.5 V RMS 1-20 KHz	\$62
3	Power Turbine Speed Set (N ₂)	0-90 Degrees	Resolver	360°	± 1.0%	0.9	1.5	6.3 V RMS 1-20 KHz (Not Critical)	Typically 1.5 V RMS 1-20 KHz	\$75
4	Power Lever Angle (PLA)	40-100 Degrees	Resolver	360°	± 1.0%	0.9	1.5	6.3 V RMS 1-10 KHz (Not Critical)	Typically 1.5 V RMS 1-20 KHz	\$75
5	Power Turbine Speed (N ₂)	4500 RPM	Subminiature Magnetic Pickup	>100,000 rpm	± 0.00%	0.3	0.7	None	1.7 to 3.2 V RMS at Speed Frequency	\$10
6	Gas Generator Speed (N ₁)	4000 RPM	Subminiature Magnetic Pickup	>100,000 rpm	± 0.00%	0.3	0.7	None	1.7 to 3.2 V RMS at Speed Frequency	\$10
7	Inlet Guide Vane Angle (IGV)	0-60 Degrees	Resolver	360°	± 1.0%	0.9	1.5	6.3 V RMS 1-10 KHz (Not Critical)	Typically 1.5 V RMS 1-20 KHz	\$75
B. SENSORS BUILT INTO GROUND TEST UNIT										
8	Atmospheric Pressure (P ₁)	8 to 16 PSI	Potentiometer Absolute Pressure	0 to 20 psi	± 2.0%	2.5	2.0	10 VDC	10 VDC Max.	\$180
9	Atmospheric Temperature (T ₁)	-65° to 135° F	Thermistor Network	-80° to 150°F	± 3.0%	0.2	0.4	10 VDC	5 KΩ Range	\$20

accuracy, range, power input, size, weight, cost, etc. The cost of the sensors also includes the estimated cost of installation and calibration.

The location of the built-in sensors in the fuel control unit and the means by which they are coupled to the hydro-mechanical mechanisms are depicted schematically in Figure 34. The mechanical means for coupling the three sensors measuring angular position and the sensor measuring metering valve position already exist in the control unit, so these sensors can be directly connected to the control unit. The speed sensors require no direct mechanical coupling and need only be inserted at appropriate locations. The ΔP sensor can be mounted on the outside surface of the control unit and receives regulated pressure through ports already provided in the control unit housing. Sensor coupling requirements, therefore, have only a negligible impact on control unit size, weight and cost.

The cost, size and weight of off-the-shelf sensors in lots of 250 units were obtained from various manufacturers' brochures, and this data, including assembly and test cost, is tabulated in Table VII. To these values we must add the cost, size and weight of the connector and harness. The increase in cost, size and weight per control unit, due to sensor installation, is:

	<u>Cost</u> <u>(\$)</u>	<u>Size</u> <u>(cu in.)</u>	<u>Weight</u> <u>(lb)</u>
Built-in Sensors	402.00	7.8	0.57
Connector and Harness	<u>10.00</u>	<u>3.0</u>	<u>0.25</u>
Total per Control Unit	412.00	10.8	0.82

The sensors located in the GSTU impact control unit cost indirectly but do not change the control unit size and weight.

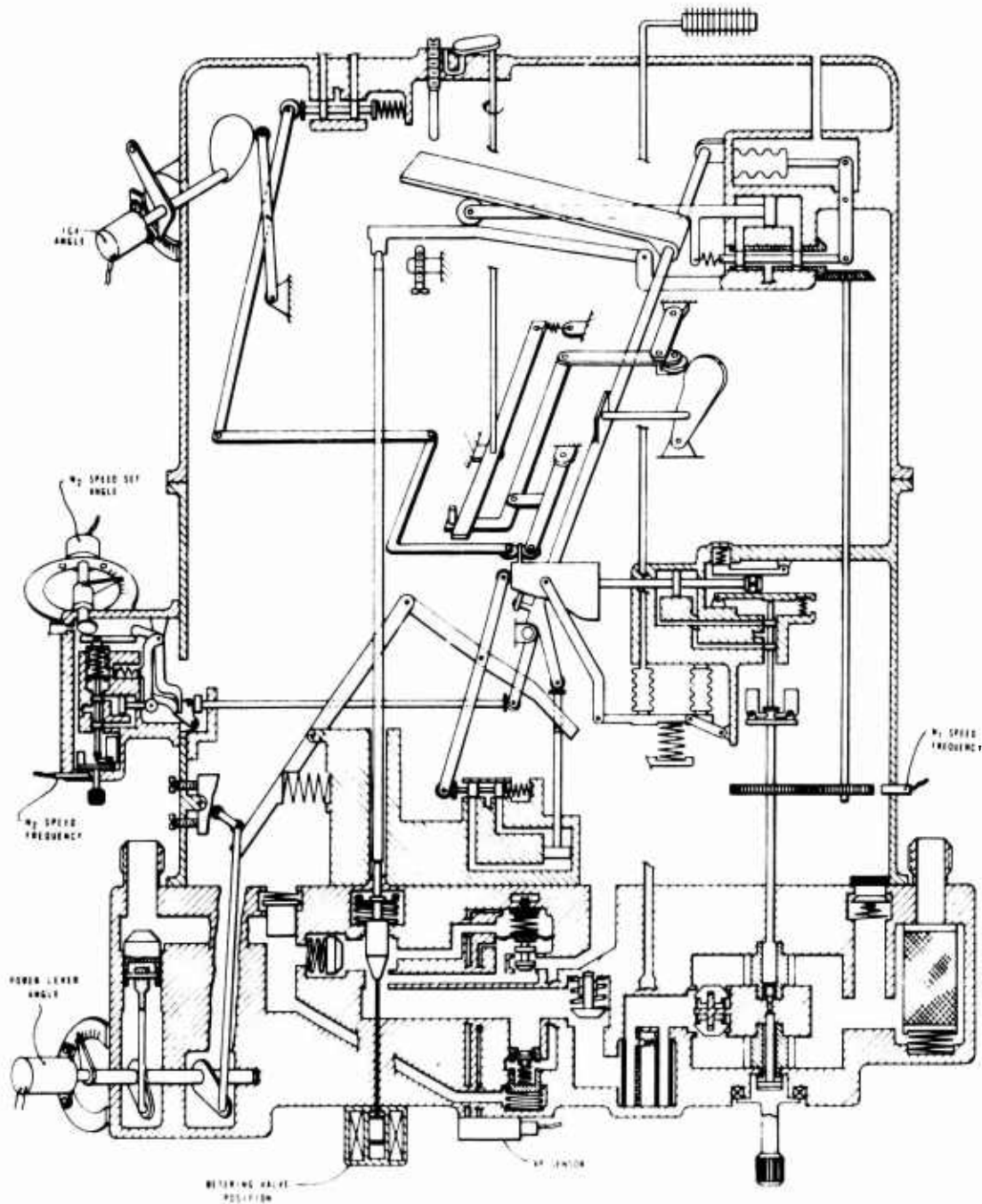


Figure 34. Hydromechanical Fuel Control With Built-in Sensors.

Electronics

The primary function of GITE electronics is to compute, from the control and atmospheric input signals, the correct metering valve (fuel flow) and IGV positions, to compare the computed values with measured values, and to indicate to the operator whether the measured outputs are within or outside acceptable error limits.

To provide this function, the GITE must include in its electronics an accurate simulation of the fuel control system functions. Referring to the system block diagram, Figure 32, fuel control simulation is supplied by the Fuel Control Model Reference Unit, and fault-isolation signal processing is provided by the Failure Detector in the GSTU.

A functional block diagram which includes both the fuel control simulations and the fault isolation is given by Figure 35. The functional block diagram details the mathematical operations which must be performed by the electronics to provide fault isolation. Each block generates an output related to its input(s) by the graphical or algebraic function included in the block. Most of these are arbitrary functions of one or two input signals. The input/output lines represent only information flow paths and not electrical interconnections. The functional block diagram does not include signal conditioning functions, which in the actual electronic circuit design may be required to convert input signal to a form which is compatible with the operation of the function generating circuits. These functions are largely included in the Sensor Excitation and Signal Conditioning unit of the GSTU.

The fuel control simulation generates output signals proportional to the desired metering valve and IGV positions, for checking the performance of the control during acceleration, deceleration, N_1 governing and N_2 governing.

The measured fuel control output signals X_m , IGV, and ΔP , together with the computed desired outputs X_m^* , IGV^* , and ΔP^* , are supplied as inputs to the fault-isolation function, where they are summed to generate the error signals E_F , E_P , and E_V . These signals are measures of fuel control

performance. Each error signal is filtered to eliminate spurious transient errors due to circuit noise and dynamic mismatch. The filtered error signal is then supplied as an input to the threshold function generator. If the error signal falls within the upper (E_H) and lower (E_L) error limits, the threshold output switches to low (0). If the error signal is higher than E_H or lower than E_L , the threshold output switches to high (1). All of the threshold outputs are supplied as inputs to the OR logic and lamp driver function, which will switch the indicator to NO-GO, indicating a failed control, if any one of its inputs is high (1). If all of the inputs are low (0), the indicator is switched to GO, indicating that the control unit under test is performing correctly.

Mechanization

The basic building blocks for the GITE electronics are the solid-state modules listed in Table VIII. These modules are constructed of integrated circuits (IC) and/or discrete semiconductor devices, mounted on printed circuit boards (PCBs) and interconnected by printed wiring. Each module, using either analog, pulse width, or digital signal processing, provides a specific, though limited, computational logic or signal conditioning operation.

The GITE electronics can be constructed to provide the functions described in the preceding section by properly interconnecting appropriate computational and logic modules. Also, signal conditioning can be provided where required in the electronics by incorporating the appropriate signal conditioning modules. The use of both analog and digital techniques in signal processing, and direct electrical interconnections of modules, characterizes the GITE electronics as a hard-wired hybrid computer. The cost of a hard-wired hybrid electronic computer is usually significantly lower than that of a programmable digital electronic computer providing the same functions.

Table VIII summarizes the function, operation and construction of each module used in the GITE electronics design. Because modular functions are relatively simple, they can be generated either by known electronic circuits or by

TABLE VIII. TEST CONTROL UNIT ELECTRONIC MODULES

Module	Construction	Function	Accuracy (% F.S. Error)	Number Required per Test Set	Production Cost per Module (Dollars)	Production Cost per Test Unit (Dollars)
DC Power Supply	Off-the-Shelf standard modules constructed of IC and discrete components, bracket ass'y.	Converts ground power (AC or DC) into ± 15 VDC and +5 VDC. Regulated power supplies for test unit electronics.	± 1.0	1	70.00	70.00
Oscillator	Crystal controlled IC oscillator. Hybrid construction.	Generates square wave at clock (Ref.) Freq. from +5 VDC, includes countdown circuits.	± 0.005	1	20.00	20.00
Sine/Cosine Generator	Discrete & IC components, PCB assembly.	Generates sine/cosine signals from osc. sq. wave for driving resolvers	± 0.1	1	27.00	27.00
DC Output Amplifier	Discrete & IC components, PCB assembly.	Amplifies low level DC signal.	± 0.25	2	20.00	40.00
Phase Demodulator	Discrete components, PCB assembly.	Converts LVDT AC signal into DC output signal.	± 0.25	1	30.00	30.00
Phase Shift to DC Converter	Discrete & IC components, PCB assembly.	Converts the phase difference between resolver AC input and output signals into DC output signal.	± 0.25	3	15.00	45.00
Frequency to DC Converter	Discrete & IC components, PCB assembly.	Converts square wave input signal into DC output signal proportional to square wave frequency.	± 0.25	2	5.00	10.00
DC to Frequency Converter (VCO)	Discrete & IC components, PCB assembly.	Converts DC input signal to proportional square wave frequency in output signal.	± 0.25	3	20.00	60.00
DC to Pulse Width Converter	Discrete & IC components, PCB assembly.	Converts DC input to proportional square wave pulse width synchronized with clock frequency.	± 0.25	4	20.00	80.00
Thermister Signal Processor	Discrete & IC components, PCB assembly.	Converts change in thermister resistance due to temperature to an output voltage proportional to $\sqrt{\theta}$.	± 0.25	1	10.00	10.00
Speed Signal Processor	Discrete & IC component, PCB assembly.	Converts low-level, sinusoidal speed signal to square-wave signal with same frequency.	± 0.1 or better	2	20.00	40.00
Phase Shifter	Discrete & IC components, PCB assembly.	Generates phase shift in AC input signal.	± 1.0	4	3.00	12.00
Voltage Gain Network	Discrete components, PCB assembly.	Provides reference DC bias signals for self test, hydromechanical control simulation, and fault-isolation electronics	± 0.25	13	0.50	6.50
Self-Test Switch	Push-button switch	Switches test control unit into self-test operation	Not Applicable	1	10.00	10.00
Mode Switches	Ganged push-button switch bank	Enables selection of one of six test modes.	Not Applicable	1	10.00	10.00
Power Switch	Push-button switch	Switches power ON or OFF	Not Applicable	1	5.00	5.00

TABLE VIII. (Cont.)						
Module	Construction	Function	Accuracy (% F.S. Error)	Number Required per Test Set	Production Cost per Module (Dollars)	Production Cost per Test Unit (Dollars)
2-D Function Generator	Discrete & IC compo- nents, ROM's for coupler functions, PCB assembly.	Generates a DC output signal which is a prepro- grammed function of a single DC input signal	± 0.5 to ± 5.0 depending on func- tion	6	120.00	720.00
3-D Function Generator	Discrete & IC compo- nents, ROM's for complex functions, PCB assembly.	Generates a DC output signal which is a prepro- grammed function of two inputs, one of which is a DC signal and the other a frequency modulated signal.	± 0.5 to ± 5.0 depending on func- tion	4	150.00	600.00
Multiplier	Discrete & IC compo- nents, PCB assembly.	Provides DC output pro- portional to the product of a pulse width input signal with a frequency input signal.	± 0.25	4	50.00	200.00
Integrator	IC and discrete compo- nents, PCB assembly.	Provides DC output which is proportional to the time integral of the DC input signal.	± 2.0	1	6.00	6.00
Summer	Discrete & IC compo- nents, PCB assembly.	Generates DC output which is proportional to sum or difference of DC input signals.	± 0.25	7	5.00	35.00
Signal Select	Discrete & IC compo- nents, PCB assembly.	Provides DC output sig- nal which is either the highest or the lowest of two or more DC input signals.	<0.01	4	10.00	40.00
Low-Pass Filters	Discrete components, PCB assembly.	Filters noise and tran- sients in input signal.	<0.01	1	1.50	1.50
Comparators	IC component.	DC output signal is switched "high" or "low" depending upon which of two DC inputs exceeds the other.	<0.01	6	5.00	30.00
Nor Gates	IC component	Switches output signal to "LOW" if any one of two or more input signals are "HIGH".	Not Applicable	1	3.00	3.00
Lamp Driver	Discrete components, PCB assembly	Supplies current to lamp filament when DC input signal is switched to LOW.	Not Applicable	2	5.00	10.00
Lamp Assembly	Includes lamp holder and lamp	Indicates GO or NO-GO condition to operator.	Not Applicable	2	1.00	2.00
TEST CONTROL UNIT COST TOTAL =						\$2,123.00

off-the-shelf electronic components. Therefore, reasonably good estimates of their cost and accuracy can be made. The accuracy, number required and estimated cost per module are given for each module listed in Table VIII. The cost per module also includes assembly and calibration costs. From this data the total cost of the GITE electronics is estimated and given at the bottom of Table VIII. Since the GSTU includes atmospheric sensors (see Table VII), and the interconnecting cable as well as the GITE electronics, the cost of these components must be added to the cost of the electronics to obtain the total cost of the GSTU estimated below.

<u>Component</u>	<u>Total Cost (\$)</u>
Electronics	2,123.00
ATM. Sensors	200.00
Connecting Cable	<u>27.00</u>
Total Cost of GSTU	2,350.00

The GSTU can be shared by up to five aircraft or up to seven control units including two spares; therefore, its cost per control unit is one-seventh of its total cost, or approximately \$336.00. Adding this value to the previously estimated cost of the control unit built-in sensors gives the total cost per control unit for the GITE fault-isolation system, estimated below:

<u>Component</u>	<u>Cost per Control Unit (\$)</u>
GSTU	336.00
Built-in Sensor	<u>412.00</u>
Total Cost per Control Unit of GITE	748.00

Operation

Figures 36, 37, and 38 are modular block diagrams of the Sensor Excitation and Signal Conditioning Model Reference Unit, and Failure Detector Components of the GITE system. The purpose of the modular block diagrams is to illustrate

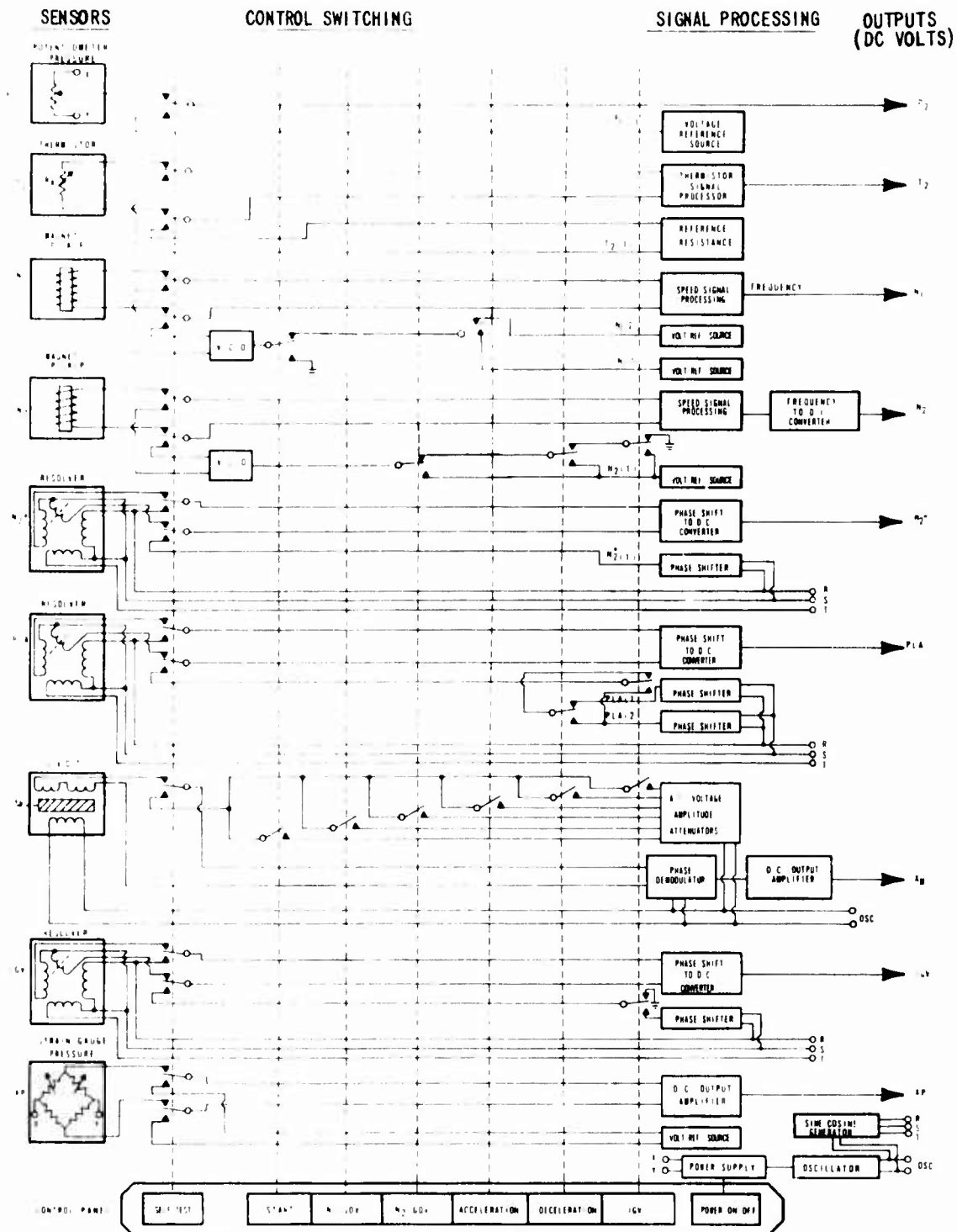


Figure 36. Sensor Excitation and Signal Conditioning Modular Block Diagram.

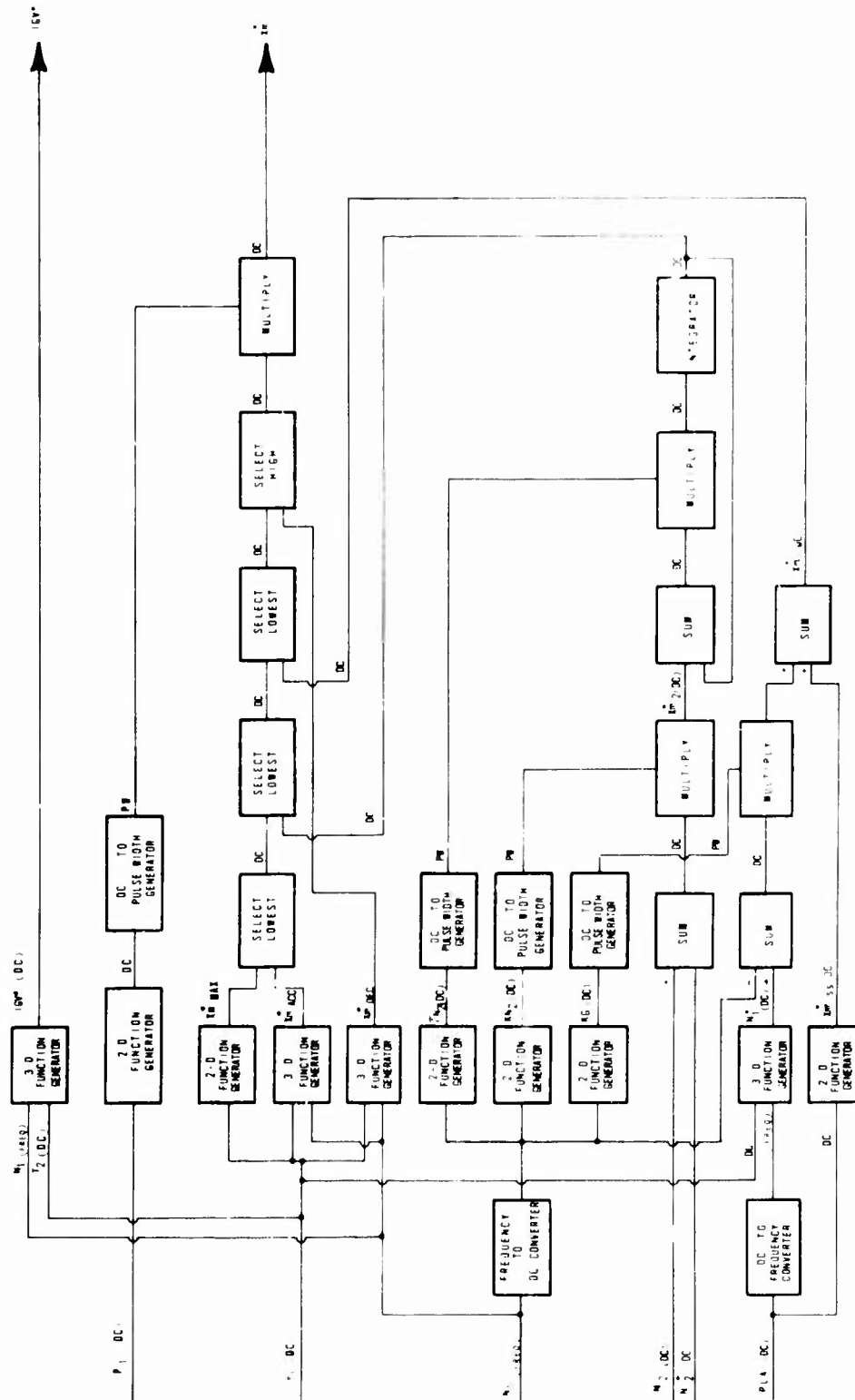


Figure 37. Fuel Control Model Reference Unit Modular Block Diagram.

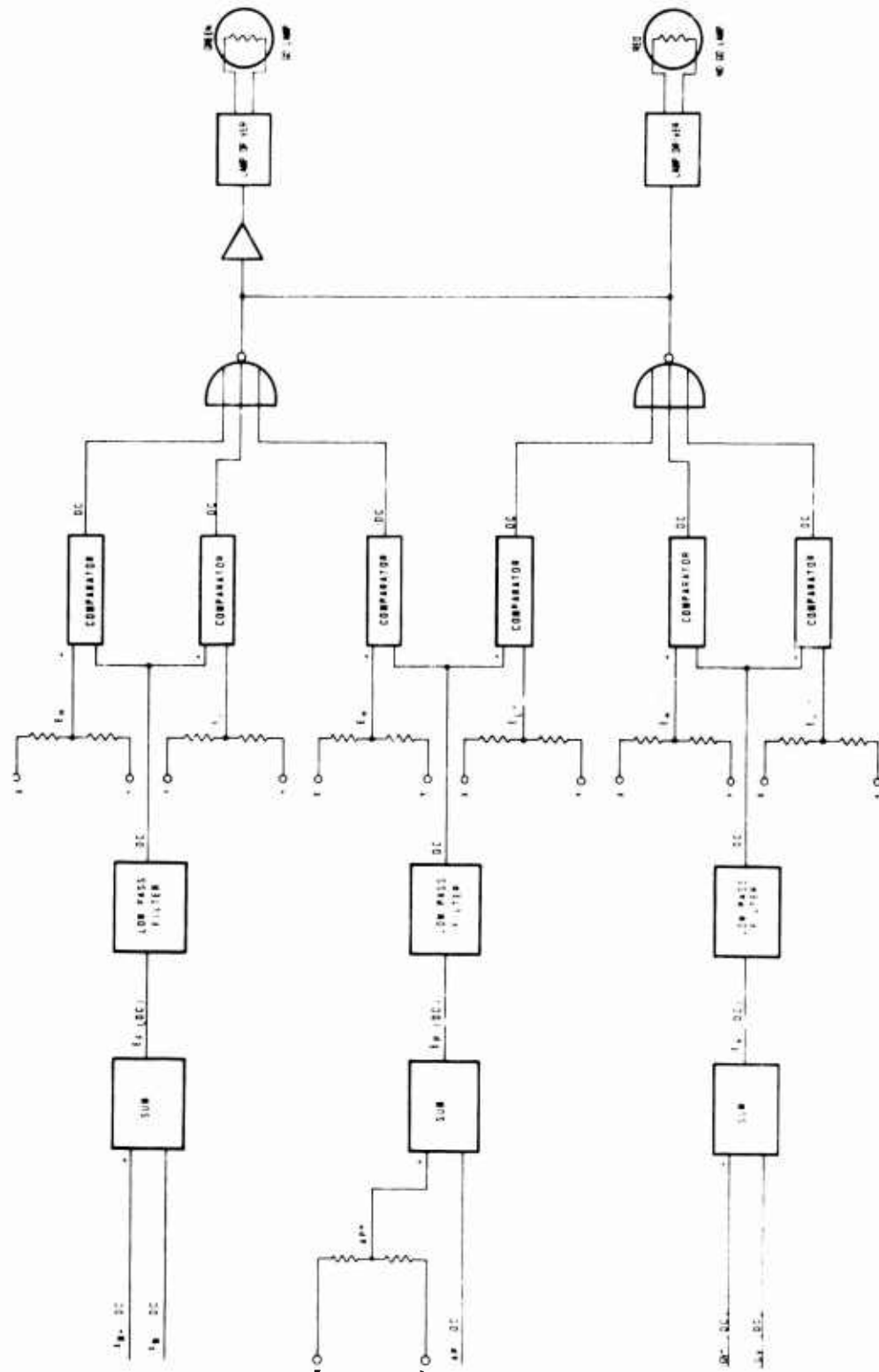


Figure 38. Failure Detector Modular Block Diagram.

the electronic modules and interconnections necessary for generating the functions given in Figure 35. Unlike the functional block diagrams, the modular representation includes the signal conditioning required to convert input signals into a form compatible with the signaling requirements of the computational and logic modules. Also, input/output lines correspond to actual electrical signal paths, although power and ground connections and specific wiring data are not included.

Sensor output signals are, in general, not directly applicable as inputs to the model reference unit electronics. The single exception is the P_2 sensor, which provides a high-level DC. The remaining sensor signals are converted into usable forms in the Sensor Excitation and Signal Conditioning Component of the GITE System. The modules providing these conversions are illustrated in Figure 38. This component also includes control switching and self-test circuits, which are discussed in the next section.

The function of the Fuel Control Model Reference Unit is to generate the desired metering valve position X_m^* and the IGV position IGV^* . Figure 37 illustrates how the electronic modules are used to compute these output signals. The electrical interconnections in Figure 37 are labeled the same as their corresponding information flow paths given in the functional block diagram for the model reference unit on Figure 35. In addition, the modular block diagram also indicates the signal form (DC, PW, or FREQ).

Signal conditioning modules are also included in the model reference unit electronics. These are required because some of the computational modules require input signals in a form other than DC, although they all generate a DC output signal.

As an example, the acceleration function $X_m^*_{ACC}$ is generated as a DC output, whereas the inputs to the acceleration function generator (see Table VIII for an explanation of the operation of this module) include a DC signal corresponding to measured inlet temperature T_2 , and a frequency modulated signal corresponding to measured gas generator speed (N_1). Similarly, the select high-output-mode signal is supplied as a DC signal to the multiply

module, and the signal corresponding to the P_2 pressure is a PW signal. Since the P_1 pressure function is generated as a DC signal by the 2D function generator, it is necessary to first convert it into a PW signal by including a DC to pulse width generator. The output of the multiply module is a DC signal corresponding to the desired metering valve position X_m^* .

Figure 38 gives the modular design of the failure detector component. In this component, all inputs, signals, and signal processing are in DC form. The desired and measured control unit output signals are supplied to the (+) and (-) inputs of the SUM module. The output of the SUM module is the error signal. The low-pass filter, which is treated as a separate module, can also be included in the SUM module. The filtered error signal is compared to a high and a low threshold value. If the error signal is greater or less than the threshold values, then one of the two comparators will switch to a high output signal (1).

The outputs of all the comparators are supplied to the OR logic circuit, which consists of two NOR gates whose outputs are connected to effect a single NOR function. This output is supplied directly to the NO-GO lamp driver and to the GO lamp driver through an inverter circuit. If all the logic inputs are low, indicating that all error signals have passed the threshold test, then the NOR circuit's output is high and the lamp driver supplying the NO-GO lamp will switch its current OFF. Since this NOR circuit output signal is inverted before being supplied to the GO lamp driver, this lamp driver will receive a low input and thereby switch the GO lamp current ON. If any one of the error signals fails the threshold test, then the NOR circuit output signal will be low, thereby switching on the NO-GO lamp current and switching off the current to the GO lamp by the logic described above.

Self Test

The GSTU is provided with a self-test feature which is incorporated in the sensor excitation and signal conditioning component (see Figures 32 and 36). The self-test

feature enables the maintenance personnel to check out the GITE for correct operation before using it to test the control unit. The self-test check is included in the normal maintenance procedure and immediately precedes the control unit test. This will ensure a high level of confidence in the control unit test results.

The self-test procedure is best described by referring to Table IX, which gives the switching requirements for self test, and to the modular block diagram, Figure 36. The operator places the GITE into self-test operation by pressing the self-test push-button switch on the control panel. This action switches the GSTU sensed parameter input lines from the sensor signals to the self-test sensed parameter settings. The sensed parameter settings are provided as bias signals in the GITE electronics (see Figures 36 and 37). The particular bias signal that is switched on to each sensed parameter input line depends upon which self-test operating mode switch is actuated. The operator can select any of the six self-test operating modes by pressing the appropriate push-button switch. The mode select switches are mechanically interconnected so that one of the six switches is always closed. The particular set of bias signals provided for a selected mode is processed by the GITE electronics as legitimate sensed parameters. Since the bias signals always represent the correct sensed parameter values for the selected control mode, the GITE electronics, if it is operating correctly, should give a GO indication to the operator. If the operator receives a NO-GO indication in self-test, it means that the GITE is providing incorrect test results and should not be used to test the fuel control unit.

The self-test bias signals are scaled to be commensurate with sensed parameter values that are typical for a selected mode. The sensed parameter settings for each test mode are listed in Table IX. The operator carries out the self-test by selecting each test mode in sequence. The operator need not select test modes in any sequence, and he can repeat any of the test modes as often as he finds necessary. If he receives a GO signal for all test modes, he can proceed with the fuel control unit test. Although it is not shown in the circuitry, the IGV error signal is disabled until the IGV test mode switch is activated.

TABLE IX. SWITCHING REQUIREMENTS FOR SELF TEST

Test Mode	Sensed Parameter Settings								
	ΔP	X_m	PLA	N_2^*	N_2	IGV	P_1	T_1	N_1
Start	$\Delta P(1)$	$X_m(1)$	PLA(1)	$N_2^*(1)$	0	0	$P_1(1)$	$T_2(1)$	0
Accel	"	$X_m(2)$	"	"	0	0	"	"	$N_1(1)$
N_1 Gov	"	$X_m(3)$	"	"	0	0	"	"	$N_1(2)$
N_2 Gov	"	$X_m(4)$	"	"	$N_2(1)$	0	"	"	"
Decel	"	$X_m(5)$	PLA(2)	"	"	0	"	"	"
IGV	"	"	"	"	"	IGV(1)	"	"	"

Typically: $\Delta P(1)$ = 18 psi

PLA(1) = maximum

PLA(2) = flight idle

$N_2^*(1)$ = 90%

$N_2(1)$ = 91%

IGV(1) = 30°

$P_1(1)$ = 15 psi

$T_1(1)$ = 59°F

$N_1(1)$ = 70% (IGV closed at 55°)

$N_1(2)$ = 92% (IGV open at 0°)

DESIGN ANALYSIS

Failure Modes

With consideration of the failure modes of wear contamination, incorrect adjustments, and leakage, the T53 control was studied, the goal being to eliminate the design deficiencies and to increase the time between overhauls to 5,000 hours.

The main areas of wear of the control are evident at overhaul. They are:

Control drive spline

N_1 flyweight drive coupling

N_2 flyweight drive coupling

The solution to the control drive wear problem has already been found and demonstrated. With a material change from nitrided steel AMS 6475 to Greek Ascaloy AMS 5616, the life in service will be increased by a factor of three. It is preferable to chrome plate the wear surfaces 0.0001 to 0.0002 inch for extra corrosion and fretting resistance. The design of the control drive shaft is shown on Figure 39.

The N_1 and N_2 flyweight drive coupling wear is due to fretting. The solution to this problem is to increase the area of engagement of the coupling. The designs for both the N_1 and N_2 coupling have been demonstrated and are shown on Figures 40 and 41.

Another problem experienced on the T53 control is with the P_2 bellows. The main problem is due to long-term growth which causes a decrease in fuel flow. A secondary problem is shift in calibration with change in air temperature. The bellows is a phosphor bronze soldered assembly, and investigation showed that the growth problem was due to chemical reaction of the zinc chloride flux with the copper base bellows material, and also the reaction of the flux with the silicone oil which is used for vibration damping. The bellows calibration shift with air temperature was due to the ingress of air during the evaluation process.

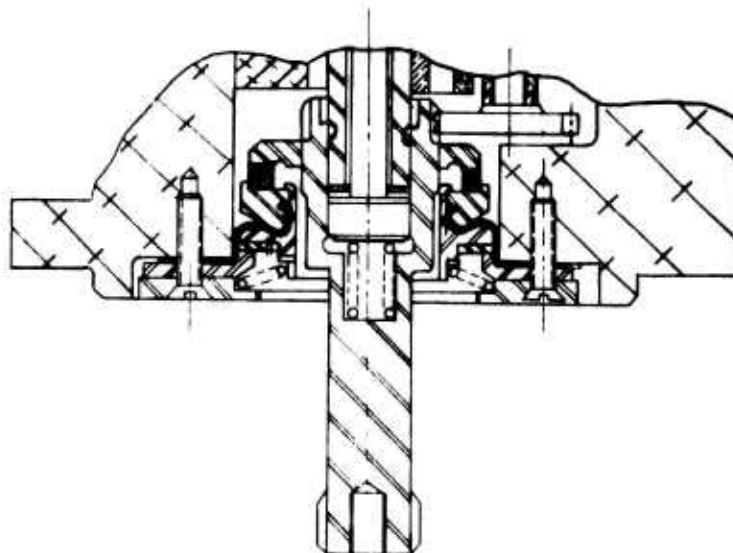


Figure 39. Control System Drive Shaft (AMS 5616)
(TA-2 Control Model).

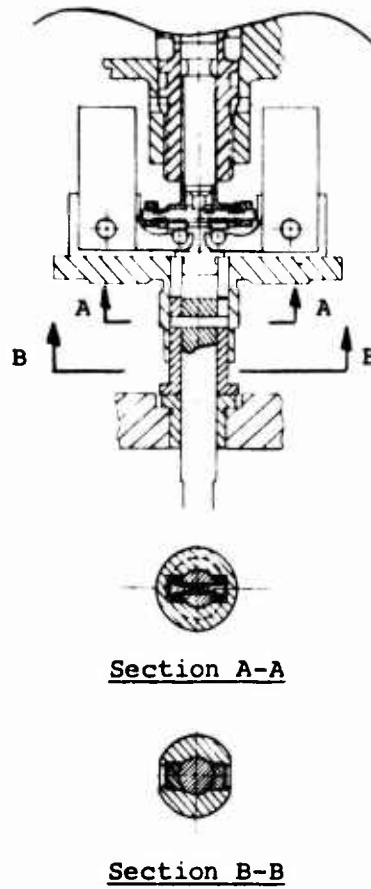


Figure 40. Gas Generator Governor Drive Coupling Modification (TA-2 Control Model).

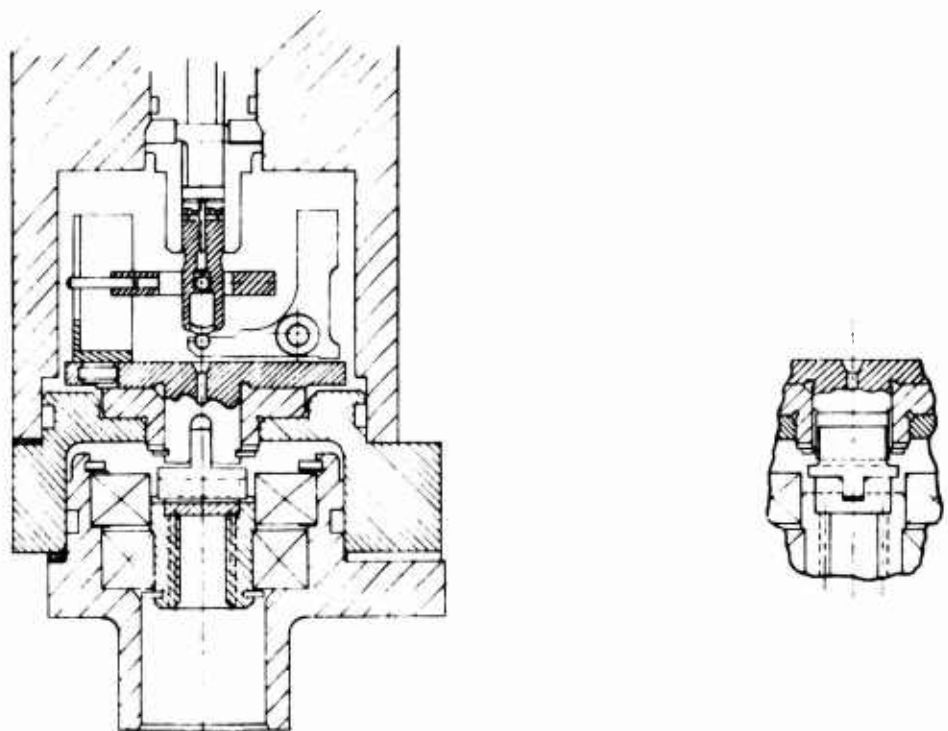


Figure 41. Power Turbine Governor Drive Modification
(TA-2 Control Model).

The bellows problem has been demonstrated to be solved by using a stainless steel welded assembly as shown on Figure 42. This design has successfully completed extensive endurance cycling and vibration testing.

It is to be noted that the control drive, N_1 and N_2 fly-weight coupling, and P_2 bellows changes were submitted individually and finally by Lycoming in a package on August 22, 1972. The recommended changes could all be introduced at overhaul.

It is estimated that with the incorporation of the above changes, a time between overhauls of 5,000 hours would be possible except for the remaining problems of seal leakage and fuel contamination. The effect of fuel contamination can be seen by comparing the T53 control in commercial service, with a TBO of 2,500 hours, with an identical unit in military service, with a TBO of 1,800 hours.

The cost savings that result from requiring less control overhauls is \$12,400 per control for the life of a control, considering that the control has a 10-year life, 500 flight hours per year, and a TBO of 5,000 hours.

Aircraft Mishaps Reported as Being Caused by the Gas Turbine Fuel Controls

An attempt has been made to determine if design deficiencies exist which make control systems unsafe. USAAVS, Fort Rucker, provided aircraft mishap information in which the gas turbine control system was involved. A summary of the information is as follows:

1. The reporting period was 17 January 1967 to 13 November 1972.
2. One hundred fifty mishaps were reported (a mishap is defined as an event in the categories of accident, incident, forced landing, or precautionary landing).

3. In general, no significant damage resulted from the mishaps. However, between 2 April 1968 and 8 July 1971, 40 mishaps occurred involving total damage of \$5,150,289. The cost of the damage was in the following percentages:

50.0%	UH-1H/1B/1C & AH-1G
40.0%	OH-6A
7.5%	CH-47A/47C
2.5%	OH-58

These percentages may be directly related to the number of flight hours involved.

4. No information was given in the computerized USAAVS report to identify specific design deficiencies which may be hazardous. EIR numbers (Equipment Improvement Recommendations) were referenced in 30 of the 40 cases. However, none of these numbers could be identified at AVSCOM because of a change in the EIR numbering system.

Recommendations and Conclusions

It is concluded that a time between overhaul of 5,000 hours is realizable provided the external leakage problem is solved and ultrafine filtration is provided.

It is, therefore, recommended that a test program be set up to investigate:

1. Seal materials and seal designs
2. Ultrafine filtration

It is also recommended that a test program be set up to investigate the effects of a realistic vibration spectrum on the control system calibration. It is usual to provide a vibration search for resonances. However, it is thought that some of the failures or calibration shifts in service that are not found at the initial factory calibration may be due to the effect of vibration conditions when the control is mounted on the engine and/or in the air vehicle.

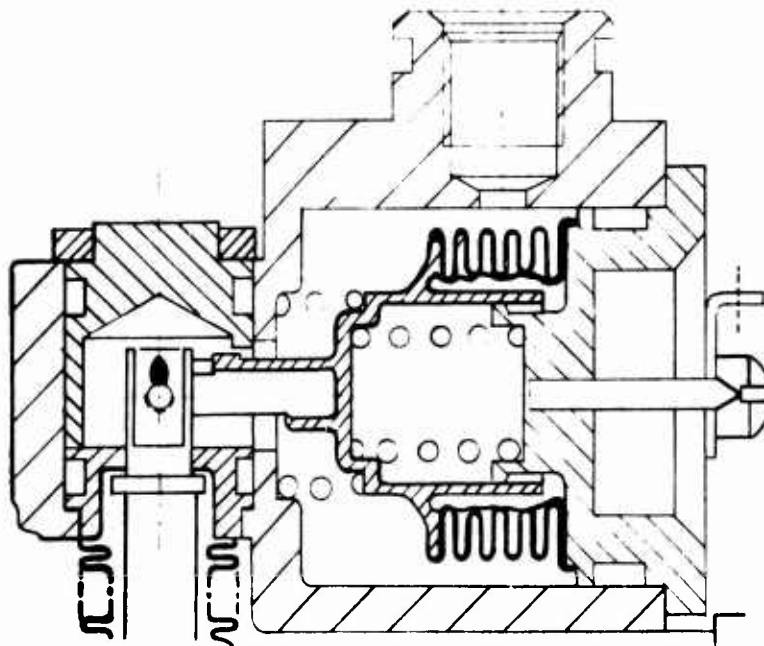


Figure 42. Welded Stainless Steel P₂ Bellows Assembly
(TA-2 Control Model).

Fault Isolation

Operational Use of GITE

A discussion of the use of the GITE in maintaining the Army's gas turbine engine fuel controls, together with its operational impact on the present maintenance requirements, is included herewith.

1. Test Procedure

At the organization level, suspected fuel control related gas turbine engine system malfunctions will be dealt with according to the following test procedure:

Upon either suspecting a control system malfunction during routine maintenance, or being informed of a suspected malfunction that occurred during a flight or preflight check-out, the maintenance technician acquires the fuel control ground support test unit (GSTU). The ground test unit is plugged into the fuel control unit and the ground support power system electrical connections. At the GSTU control panel, main power is switched on and a self-test verification routine is initiated by depressing the self-test switch. The six interlocking mode switches are depressed consecutively, with any malfunction being indicated by excitation of the red NO-GO lamp. Upon successful completion of the verification test (green GO lamp is lit), the self-test switch is depressed to the OFF position. The GTE is now ready for the operational test of the fuel control. First, the engine is cranked and, if a successful start is accomplished, run up to maximum allowable ground power. During run-up, acceleration schedules will be checked. For helicopters, the power limit is determined by selecting a rotor collective pitch that allows the

power turbine to be governed to its selected speed without causing the vehicle to lift off the ground. Generally, this will be in the region of 75 to 90% engine speed depending on aircraft load and the atmospheric conditions prevailing.

The operation of both the power turbine and gas producer governors can be checked at this part-power condition.

Finally, a deceleration to ground idle completes the fuel control test procedure. Any failure in the fuel control unit will be indicated by the red NO-GO lamp at the control panel. This includes failure to start the engine. Any failure indication can be cleared for retest by depressing the reset button. If no failure is indicated, the GTE is disconnected and returned to the crib, while troubleshooting is continued on the engine and other engine system components. If a failure is indicated, the unit is disconnected and the fuel control removed and replaced with a unit from stock.

2. System Performance

It is estimated that using GITE, the fuel control can be checked out in less than 30 minutes. No special skills are required to operate the equipment and, outside of following simple operating instructions, no training is required. Providing the equipment is not mishandled, it should operate with a very high degree of reliability, requiring a minimum of maintenance over the life cycle of the equipment. If maintenance should be required, then any qualified electronics technician with a minimum of test equipment should be able to make the repair at the organizational level. That is, no special facilities are required. Maintenance required on the fuel control installed sensors would be treated as a fuel control malfunction and require the fuel control to be removed and replaced. The selection of high-reliability sensors

should minimize the impact of these sensors on the fuel control MTBR. Finally, the elimination of unjustified removals resulting from the use of this equipment will result in the fuel control MTBR being increased from the present rate of 350-400 flight hours to 475-540 flight hours. This is based on eliminating the unjustified removals (35%) presently being experienced on Army aircraft.

SUMMARY AND CONCLUSIONS

The work conducted during this program was directed toward identifying fuel control system faults and establishing design recommendations for Army gas turbine engine fuel controls which will reduce the high rate of unjustified and unscheduled removals and increase the design life of future fuel controls.

Failure modes common to present Army fuel control and responsible for approximately 50% of the justified removals were identified based on surveys and in-house data. These faults include fuel and air contamination problems, fuel seal leaks, drive spline wear, and improper adjustments. Test and development work previously conducted indicates that chrome-plated, Greek Ascaloy drive shafts will solve the drive spline wear problem if proper wet lubrication is provided. Fuel and air contamination problems can probably be solved by providing ultrafine filtration. However, the filters will be large, and pneumatic computer systems are sensitive to pressure losses in the filter. The only known solution to the improper adjustment problem is to eliminate all external adjustments. The fuel seal problem will require test and development of various potential seal material combinations.

Studies were conducted to establish a cost-effective fault-isolation scheme which would eliminate the 30 to 50% unjustified removal rate of fuel controls. Based on a life-cycle cost analysis, it was determined that a 95% effective fault-isolation device would be cost effective if its selling price was about 10% of the price of the fuel control.

Preliminary design studies of various possible fault-isolation concepts concluded that effective fault isolation of the control can be accomplished only by performing a functional test of the fuel control system. For present-day fuel controls, ground support type equipment which can be shared by at least five aircraft was determined to be the only cost-effective approach to fault isolating the fuel control.

Studies completed on built-in fault isolation for an advanced electronic control indicated that this concept could be cost effective. Moreover, future electronic control systems will be field replaceable modular constructions. One of these modules will be the fuel pumping and metering section of the

control. Fault isolating this module can be done by sensing the metering head pressure drop. Any fault in this module that results in a malfunction of the engine will be evidenced by a variation in the pressure drop across the metering valve.

The potential exists for future fuel control systems providing 5,000 hours of operation between overhauls. This can be accomplished if proper filtration and seals can be developed, if recommended design improvements are introduced to eliminate generic faults, and if effective fault isolation is provided. Although commercial users experience the same high rate of unjustified removals as the Army, TBO's for fuel controls in commercial application are in the 2,500-hour range, and these fuel controls are identical to those used on Army gas turbine engines. It is concluded, therefore, that successful incorporation of the recommended improvements should make the 5,000-hour goal attainable.

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